FEASIBILITY OF ROOF TOP SOLAR PHOTOVOLTAIC (PV) SYSTEM FOR KFUPM BUILDINGS

BY

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Dedication

I would like to dedicate this humble work to my beloved parents. To my affectionate mother and father for their endless help and support. They granted me the love that made me strong enough to continue my higher education.

I would also like to dedicate this thesis to my lovely brothers (Hadi and Eihab), whom I consider as my best friends.

I also dedicate this work to my grandmother, who unfortunately passed away four months before the completion of this work. May Allah have mercy on her and grant her the eternal paradise.

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All praise is due to Allah, The Most Beneficent, and The Most Merciful. The Almighty, with whose gracious help it was possible to accomplish this work.

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LIST OF ABBREVIATIONS

AC	:	Alternating current
ALCS	:	Annual life cycle savings
BCR	:	Benefit to cost ratio
BIPV	:	Building integrated photovoltaic
COE	:	Cost of energy
CSP	:	Concentrated solar power
DC	:	Direct current
EIA	:	Energy Information Administration
ERI	:	Energy Research Institute
FIT	:	Feed-in Tariff
GHG	:	Greenhouse Gas Emissions
HVAC	:	Heating, Ventilating, and Air Conditioning
IRR	:	Internal rate of return
KACST	:	King Abdul-Aziz City for Science and Technology
KAUST	:	King Abdullah University of Science and Technology

KFUPM	:	King Fahd University of Petroleum and Minerals
KSA	:	Kingdom of Saudi Arabia
MOHE	:	Ministry of Higher Education
NPV	:	Net present value
NRE	:	New Renewable Energy
PI	:	Profitability index
PV	:	Photovoltaic
PVT	:	Photovoltaic and thermal (PVT) collector technology
R&D	:	Research and Development
SPP	:	Simple payback period
STC	:	Standard test conditions
YPCF	:	Years to positive cash flow

ABSTRACT

Full Name : Haitham Feras Sawalha

Thesis Title : Feasibility of Roof Top Solar Photovoltaic (PV) System for KFUPM Buildings

Major Field : Architectural Engineering

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Buildings through their energy and materials consumption have an important contribution in the global energy and environmental scenario that faces serious challenges. Saudi Arabia has one of the highest per capita energy and environmental emissions. The buildings sector accounts for almost 80% of the total national electricity consumption. To address the energy and environmental problems facing the country, it is important to promote sustainability in the building sector. Renewable energy can be an effective solution to provide environmentally friendly energy to buildings. The kingdom of Saudi Arabia has rich potential for solar energy. Solar photovoltaic (PV) can be an appropriate technology to harness the immense solar potential. This study focuses on the assessment of solar PV potential in the King Fahd University of Petroleum and Minerals (KFUPM), one of the largest universities in the kingdom. It employs PVsyst and RETScreen programs to investigate the potential for solar PV on the rooftops of the entire campus buildings, offering 505,164 m^2 of total rooftop areas. Optimization for PV installation is done for the power generation between tilted and horizontal PV systems. The findings of the work reveal that application of PV systems on the KFUPM building rooftops can produce 37,746 MWh/year and 46,047 MWh/year for tilted and horizontally installed PV systems respectively. This amount of generated energy respectively covers 16.4% and

20% of KFUPM's total electricity consumption. The study also investigated the economic feasibility of the two installation options using various economic parameters such as benefit to cost ratio (BCR), simple payback period (SPP), and equity periods. Finally, an estimation of the greenhouse gases (GHG) emissions as an environmental feasibility analysis was carried out. It was calculated that the utilization of tilted PV systems save the environment from 32,952 tons CO_2/year, and the horizontal PV systems save it from 40,199 tons CO_2/year.

ملخص الرسالة

الاسم الكامل: هيثم فراس صوالحة

عنوان الرسالة: دراسة جدوى استخدام الخلايا الكهروشمسية على أسطح المباني في جامعة الملك فهد للبترول والمعادن

التخصص: الهندسة المعمارية، هندسة البناء.

تاريخ الدرجة العلمية: أيّار 2015

إن المباني ومن خلال استهلاكها للطاقة والمواد تلعب دورا مهما من خلال مساهمتها في سيناريوهات الطاقة والبيئة العالمية والتي تواجه تحديات كبيرة هذه الأيام. المملكة العربية السعودية لديها واحد من أعلى معدلات الطاقة للفرد والانبعاثات البيئية. حيث إن قطاع الأبنية لوحده في السعودية يساهم في 80% من اجمالي استهلاك الكهرباء على الصعيد الوطني. ولمعالجة مشاكل الطاقة والمشاكل البيئية التي تواجه البلاد، فإنه من المهم تعزيز مفهوم الاستدامة في قطاع البناء. إن مصادر الطاقة المتجددة يمكن أن تشكل حلا فعّالا لتوفير الطاقة الصديقة للبيئة للمباني. تمتلك المملكة العربية السعودية إمكانيات غنية من الطاقة الشمسية. إن الخلايا الكهروضوئية هي التكنولوجيا الملائمة للاستفادة من هذه الإمكانيات الهائلة في المملكة. وتركّز هذه الدراسة على تقييم إمكانيات الطاقة الشمسية للخلايا الكهروضوئية في جامعة الملك فهد للبترول والمعادن والتي تعتبر واحدة من أكبر الجامعات في السعودية. لقد تم استخدام كل من برنامجي PVsyst و RETScreen في هذه الدراسة للكشف عن إمكانيات الطاقة الشمسية للخلايا الكهروضوئية على أسطح المباني في الحرم الجامعي بأكمله، وتقدّر مساحة أسطح المباني الاجمالية بـ 505,164 متر مربع. كما تم دراسة احتمالين لتركيب الخلايا الكهروضوئية: إما مائلة بزاوية معينة او افقية على الاسطح لإيجاد الخيار الأمثل لإنتاج الطاقة الكهربائية. كشفت نتيجة العمل أن تطبيق أنظمة الخلايا الكهروضوئية على أسطح مباني جامعة الملك فهد يمكن ان تنتج 37,746 ميغاواط ساعة لكل سنة او 46,047 ميغاواط ساعة لكل سنة لأنظمة الخلايا المائلة والافقية على التوالي. هذه الكمية من الطاقة المتولدة تغطي 16.4% و 20% من اجمالي استهلاك الجامعة السنوي من الكهرباء على التوالي. كما تناولت أيضا هذه الدراسة الجدوى الاقتصادية للنظامين الآنف ذكرهما وباستخدام العديد من المعايير الاقتصادية، مثل استخدام نسبة الفائدة الى التكلفة، فترة السداد

البسيطة، وفترات السداد التي تأخذ القيمة الزمنية للعملة. وأخيرا، تم عمل دراسة جدوى بيئية لحساب كميات "غازات الدفيئة" التي يمكن حماية البيئة منها. حيث ان الخلايا الكهروضوئية المائلة تحمي البيئة من 32,952 طن ثاني أكسيد الكربون سنويا، والخلايا الافقية من 40,199 طن ثاني أكسيد الكربون لكل سنة.

CHAPTER 1

INTRODUCTION

1.1 Overview

The existing global energy scenario is leading to wide ranging energy and environmental problems including depletion of fossil fuels, global warming and energy insecurity. In a business as usual scenario, these problems are likely to intensify in future. It is estimated that the global reserves for coal, natural gas and oil will last for 128 years, 54 years and 41 years respectively (World Energy Council, 2010). Given this background, if the rate of annual energy consumption as per the period from 2008 to 2035 is taken to be 1.4%, fossil fuels energy sources will be depleted in less than 50 years (Hong et al., 2013). The kingdom of Saudi Arabia mainly depends on oil as an energy source for generating electricity. Oil consumption in Saudi Arabia from its own oil production has increased over the years. KSA consumes about one fourth of its oil production, which is equal to three million barrels per day. Electricity generation in Saudi Arabia has been increasing to keep pace with the increased demand and consumption. These facts make Saudi Arabia one of the fastest growing electricity consumer in the Middle East.

Growing interests in new renewable energy (NRE) supplies is very important to face the aforementioned energy problems. In 2009, NRE accounted for 18% of global electricity generation. Moreover, it is expected that an increase of 40% in the global renewable energy generation will take place during the period 2011 to 2017 according to the ‘Medium-Term Renewable Energy Market Report 2012’. Solar energy technologies including photovoltaic (PV) are believed to have an important role in the sustainable and renewable energy development. Figure 1 (EPIA, global market outlook for photovoltaic 2013-2017) shows that the global photovoltaic market, that was 7.2 GW in 2009, has increased by almost double to 16.6 GW in 2010. As per 2011, it went up to 29.6 GW. The global photovoltaic market is growing rapidly, and it is expected to reach 62 GW in 2015. The growing PV market can contribute towards energy conservation in buildings. Utilizing photovoltaic systems will generate considerable amounts of electrical energy, which will reduce the fossil fuel-based electricity consumption. Photovoltaic systems are believed to have significant role in the application of nearly-zero energy buildings with the continuous descending trend in their costs (Hong et al., 2013).

Solar energy is considered as one of the most promising renewable energy resources. It is a sustainable source of energy that has good accessibility. In recent years, the electricity generation through the use of photovoltaic (PV) technology has greatly progressed (Hong et al., 2014 and Lewis, 2007). Photovoltaic systems can be applied in various ways; on ground or directly on buildings. In the latter case again, these can be used in various forms including façade integrated, roof mounted, roof integrated, free standing, and façade mounted systems. Many parameters need to be taken into account when trying to install rooftop PV systems (Eltawil, 2010; and Singh, 2003), as the buildings' rooftops suitability may differ from one building to another, regarding the amount of received solar irradiance. This has an important role in urban planning of modern sustainable cities and on their environmental health. Selecting the most beneficial place for photovoltaic systems' installations highly depends on the solar potential of that place (i.e. the total received solar irradiance). The total solar potential received by any surface is affected by many parameters: geographic location, topography of the surface, and atmospheric attenuation. The latter parameter occurred as a result for molecular absorption, influence of scattering, and shadowing effects from the surroundings (Lukac et al., 2013).

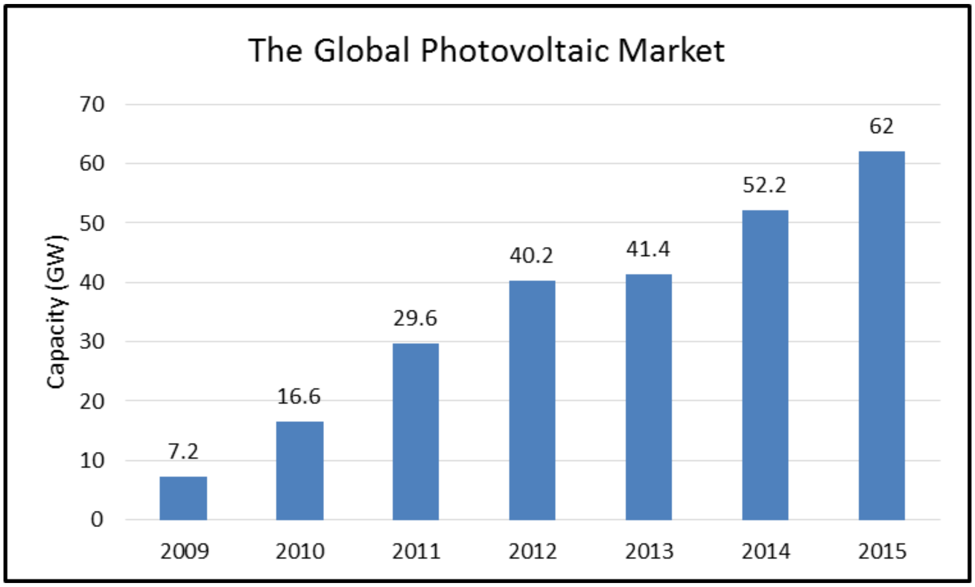


Figure 1: The global photovoltaic market 2009-2015

1.2 Problem statement

In a business as usual scenario, the energy problems primarily in the form of depletion of fossil fuels and emissions of greenhouse gases from these energy resources are set to intensify in future. Given the importance of building sector, the concerned stakeholders in this sector need to pay more attention to the environmental design aspects of buildings and application of renewable energy technologies to promote sustainable buildings.

Saudi Arabia possesses one fourth of the world's oil reserves, and it is known to be the largest oil-producing country in the world for the near future. Saudi Arabia's gas reserves are estimated to be around 204.5 trillion cubic feet making it the fifth largest country in the world in terms of these reserves. Figure 2 and Figure 3 show oil and gas production trends in Saudi Arabia. It is clear that Saudi Arabia has been increasing its oil and gas production since middle eighties (U.S. Energy Information Administration report for Saudi Arabia 2014).

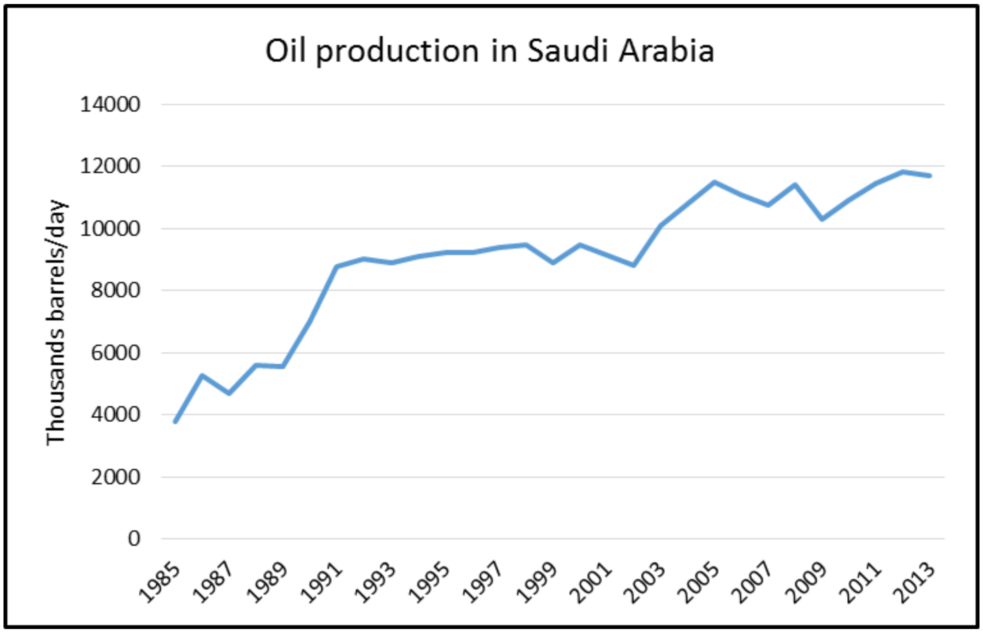


Figure 2: Oil production trend in Saudi Arabia

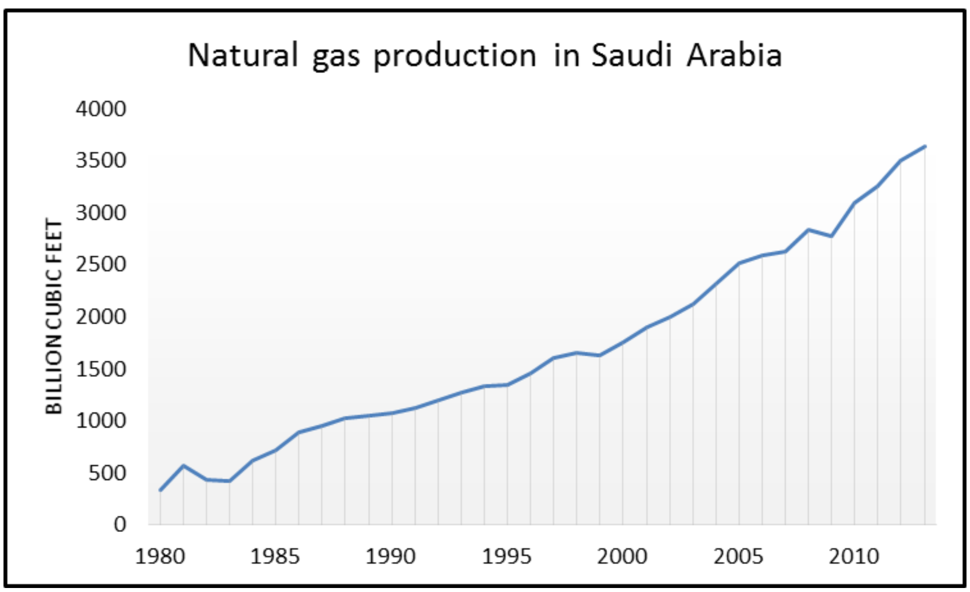


Figure 3: Natural gas production in Saudi Arabia

Saudi Arabia is a rich and developing country. The energy demand specially the electricity demand has a 5% annual growth rate (EIA, 2012). Electricity generation and consumption are presented in Figure 4 over the period 1980 - 2012. It is expected that till the year 2025, Saudi Arabia will invest around $117 billion in the power sector alone (EIA, 2012). Most of that investment will be carried out by the private sectors, attempting to expand and develop the national power grid. The United States Energy Information Administration U.S EIA, in its report on Saudi Arabia in 2012, estimated an average of 2000 MW power capacity should be provided each year until 2020.

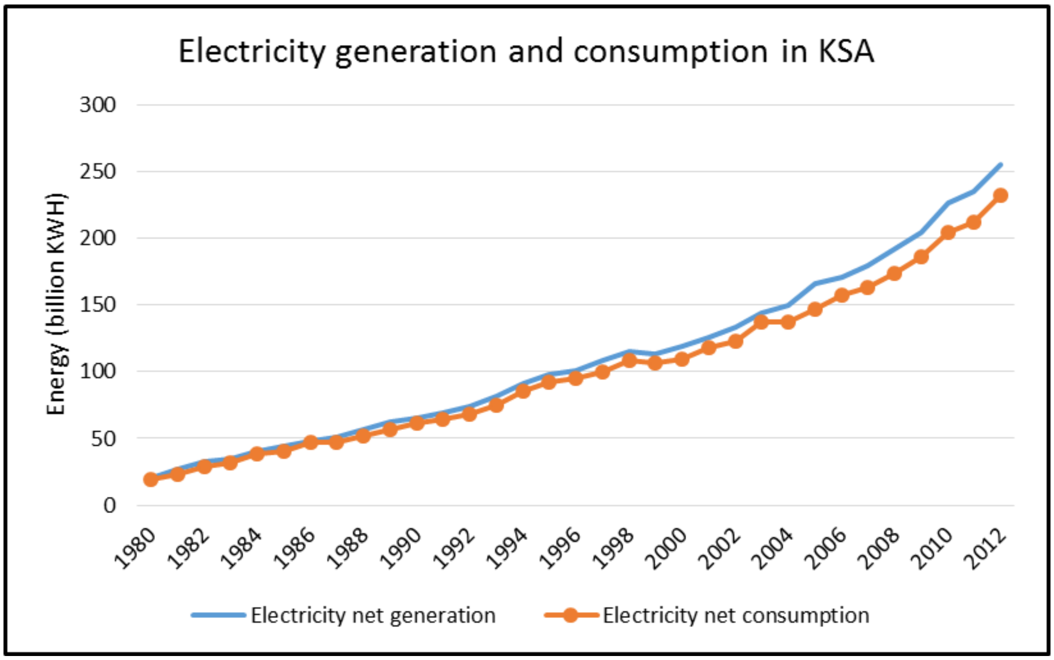


Figure 4: Electricity generation and consumption in KSA

Although the fact that Saudi Arabia owns a relatively good potential of oil and gas reserves compared with other countries in the world, the increasing demand for fossil fuel driven energy faces many problems such as depletion of resources and increased environmental issues (pollution and global warming). The output emissions of fossil fuel combustion process increase the amounts of GHG in the atmosphere. Figure 5 shows the increasing GHG emissions in terms of CO_2 equivalent in Saudi Arabia. On the other hand, the continuously growing annual demand for energy and electricity, and the need for expanding the national grid to cope with the rapid urban growth will imply huge investment costs in the power sector and consumes from the country's budget. Consequently, the need for developing energy conservation policies in Saudi Arabia becomes urgent for the sustainable development.

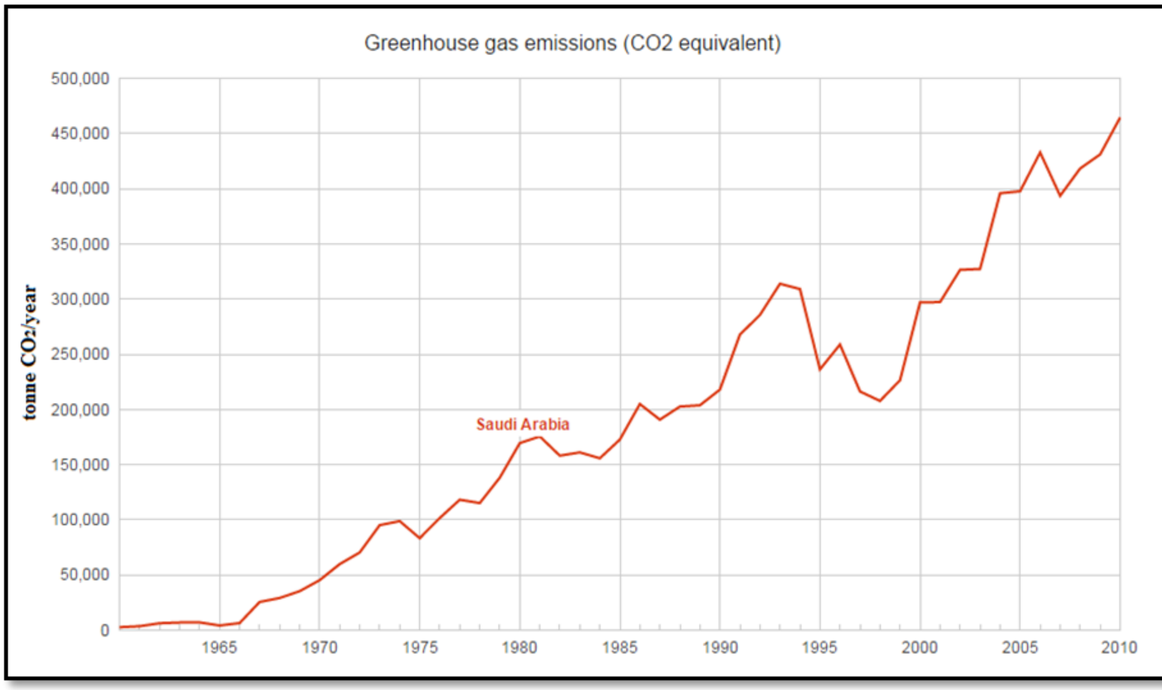


Figure 5: GHG emissions, CO_2 equivalent in KSA (Source: World Bank, 2015)

It is recognized that the renewable energy resources available in Saudi Arabia, specially the sun as a major source will play a significant role in the provision of energy for the building sector. The solar energy has the following advantages over other sources:

- It is a renewable resource
- Clean energy (no harmful emissions to the atmosphere).
- It is widely available and is inexhaustible

Saudi Arabia has a healthy potential for solar energy in terms of available solar irradiance and sunshine hours. Knowing these potential of solar energy in KSA, it is clear that this natural source of energy should be exploited as much as possible, which in turn will positively reflect on the benefit of the country. In recent years, Saudi Arabia's government and private sectors are showing keen interest in developing and utilizing solar energy. However, these efforts need to be supported and adopted on a higher scale.

1.3 Aim and objectives

This study aims at investigating the feasibility of the implementation of roof top solar photovoltaic (PV) system in King Fahd University of Petroleum and Minerals KFUPM buildings. The research will concentrate on the incident solar energy on buildings' roof top, electrical energy that could be generated from solar panels (photovoltaic), and on the economic and environmental benefits that could be achieved as a result of the generated energy.

The main objectives of this research are:

1) To assess the potential for roof top solar energy for KFUPM buildings using available weather data.

2) To design optimum installation scheme for photovoltaic (PV) systems and finding out the power generation potential.

3) To conduct an economic feasibility for rooftop PV systems.

4) To conduct an environmental analysis to find out the amounts of the greenhouse gases emissions that would be prohibited from being released to the atmosphere.

1.4 Significance of the research

This study will take the rooftops of KFUPM’s buildings into account to apply solar photovoltaic systems on it. KFUPM is located in the city of Dhahran in the Easter Province of Saudi Arabia, which has a high level of solar irradiance. The existing energy supply in KSA is all fossil fuel-based. KFUPM reflects an urban scale environment due to wide variety and large number of buildings. A small proportion of the roof top areas of these buildings are partially utilized by other applications, consequently, the university has significant areas on its buildings’ rooftops that can be utilized by solar photovoltaic systems to generate electricity.

The advantages of utilizing the buildings’ rooftop areas over other areas in the campus:

- The rooftop areas are not used by the occupants usually.
- The rooftop areas are away from any potential hazards, unlike stand-alone PV systems on the ground.
- Land acquisition costs are not needed.
- When building integrated photovoltaic (BIPV) been applied on rooftop, they shall increase the thermal resistance of the building roof, and thus improving the internal thermal comfort environment.

These reasons encourage the researcher to investigate the potential of using solar photovoltaic PV systems on the buildings’ rooftop in KFUPM campus.

This research is significant for public and private sectors interested in solar energy utilization as a good source of renewable energy in Saudi Arabia. However, its importance emerges from the following:

- This research is going to offer answers to the following questions:

- What is the current potential of KSA and Dhahran area in terms of the annual solar incident energy?
- What is the available rooftop areas in KFUPM for PV systems, taking into consideration the total areas of the rooftops and the areas that could not be utilized (HVAC systems and skylights, etc.)?
- How much electrical energy would be generated annually when utilizing PV systems on the rooftop areas in KFUPM (optimized power generation between flat and tilted PV panels)?
- Then, what is the total cost of this investment, and what is the annual monetary benefits of the generated energy?
- Arranging the priorities of utilizing the buildings' rooftops according to its categorization depending on benefit to cost ratio analysis.
- Finally, how much GHG emissions would be saved from being released to the atmosphere?

- Utilizing the generated energy from PV systems, will have a great advantage in reducing the demand for fossil fuel-based electricity in buildings at the local and national levels.
- The advantages will also be reflected in terms of reducing the greenhouse gas (GHG) emissions to the atmosphere.
- This research offers an encouragement for the energy decision makers, particularly in KFUPM, and in Saudi Arabia in general, in facilitating the endorsement of solar energy applications as a renewable energy source.

1.5 Scope and limitations

The scope of work within this research is limited to the following determinants:

1) To any building that is located within KFUPM campus.
2) Only buildings' roof top areas will be taken into consideration in this research.
3) Fixed plane solar photovoltaic systems will be used as they offer less cost if compared with solar tracking PV systems.
4) Mono-crystalline silicon cells will be used because they deliver the highest electrical efficiency over other cells types.

1.6 Thesis organization

This research thesis is mainly divided into five chapters, which in turn address the necessary information about the work. The following is a brief description of each chapter:

1. **Chapter One – Introduction**

   This chapter provides the reader with significant information about the global use of energy, and the associated environmental problems accompanying to the increasing trends towards energy consumption. It also describes the global solar energy market and utilization. The chapter also provides information about the current situation of Saudi Arabia regarding its production of electricity form both oil and gas, along with the electricity generation and consumption trends over the years. Then, the aim of the research and the proposed objectives are introduced. It also offers a brief description for the research case study, and the importance of the research represented in the outcome benefits from energy generation, economic and environmental assessment. Finally, the limitations for the research and its scope are identified.

2. Chapter Two - Literature Review

This chapter illustrates the associated literature review, starting from definitions and explanation of photovoltaic PV systems and its types and efficiencies, to its advantages, disadvantages, and applications. It also presents the feasibility of solar photovoltaic for both the world and Saudi Arabia. Then, it illustrates the interest of solar energy in Saudi Arabia as represented in the Research and Development R&D projects in the kingdom.

3. Chapter Three - Research Methodology

This research has four objectives to be accomplished in this chapter. Research methodology for each objective is explained and shown in detail making it easier for the reader to comprehend and understand how it was carried out.

4. Chapter Four - Data Analysis and Results

In this chapter, all the data pertaining the solar potential of Dhahran area in which KFUPM is located is presented. It also discusses the two cases of implementing the photovoltaic systems on the rooftop of KFUPM buildings. Firstly, the photovoltaic PV systems are installed on the roof top areas with an optimal inclination angel associated with Dhahran area. While in the second, horizontal installation is considered.

Roof top areas and their utilization with solar panels are shown in details. Finally, the results obtained from the optimization process of the pre-mentioned two cases together with the economic and environmental analysis are presented and discussed.

5. **Chapter Five - Conclusion and Recommendation**

This chapter provides the conclusions. It also provides the reader with some recommendations and suggests for prospects for future work.

6. **Appendices**

This part has the simulation results for all of the buildings’ roof top areas taking into consideration the two cases of photovoltaic PV implementation. It also has the technical specifications of the used solar systems.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Solar photovoltaic systems or solar PV systems can be simply defined as power systems, which in turn use photovoltaic technology to convert solar energy into usable electrical energy. The conversion of solar energy into electricity takes place in the solar cell, which is a semiconductor device that delivers a particular amount of electrical power when it receives solar radiation. One photovoltaic system consists of series of arrangements of the system components. These components may include:

- Photovoltaic modules or solar panels (the power generators).
- Battery (if electricity storage is needed at night or bad weather).
- Charge regulator (provide protection for batteries from overcharge or excessive discharge).
- Invertor (conversion from direct current DC into alternating current AC).
- Backup generator (backup source of energy if the system fails).

The heart of the solar photovoltaic system is represented by the solar panels that directly receive and convert light and sun rays into direct current (DC). Then comes the charge controller and the regulator, after that, the inverter of the system, it converts the generated electrical direct current DC into alternating current AC. The whole system also contains other components like wiring, cabling, batteries, and monitoring systems to put up a complete working solar power photovoltaic system. Figure 6 shows a schematic diagram of a photovoltaic system.

There are many technologies that can benefit from solar energy other than photovoltaic systems that produces electricity as mentioned before, and should not be confused with them, like concentrated solar power (CSP) and solar thermal systems, used for cooling or heating applications and for power generation.

Solar photovoltaic PV systems could be small in capacity, as implemented on a building roof top or integrated with its façade. On the other hand, it could be large capacity systems as in massive utility power stations.

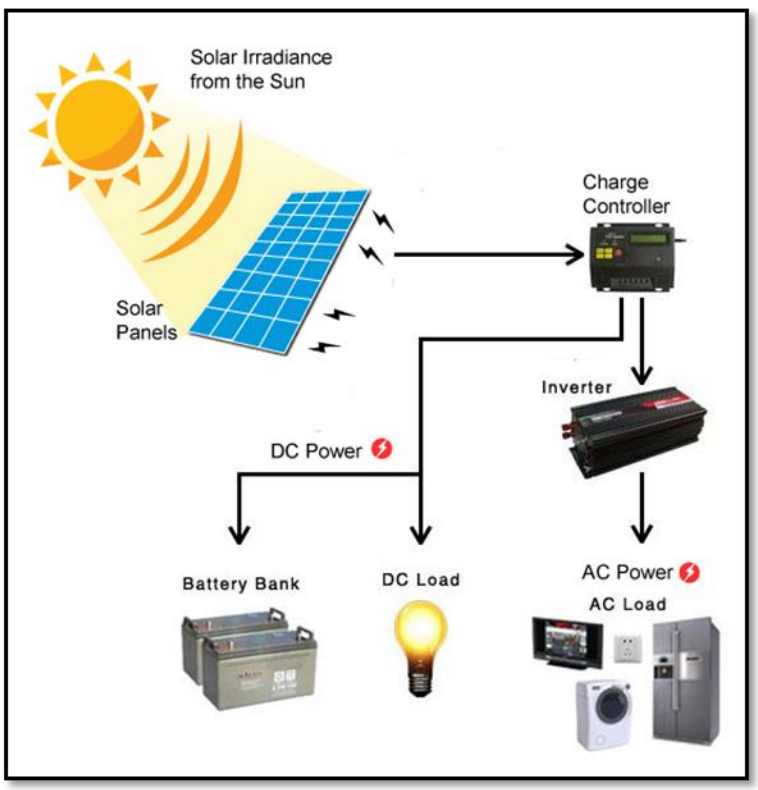


Figure 6: Schematic diagram of a photovoltaic system (Solarsorena.com, 2015)

2.1.1 Definition of photovoltaic PV

In very simple words, photovoltaic can be defined as the technology that directly converts solar energy or sunlight into usable electricity without using any mechanical or heat engine. Each photovoltaic panel consists of many smaller components called solar cells. These cells are connected together physically and electrically by means of several connections to form a module. Then modules are linked to produce a solar panel. When several solar panels are connected to each other, they form a solar array; Figure 7 explains the relationship between solar cells, modules, panel and array.

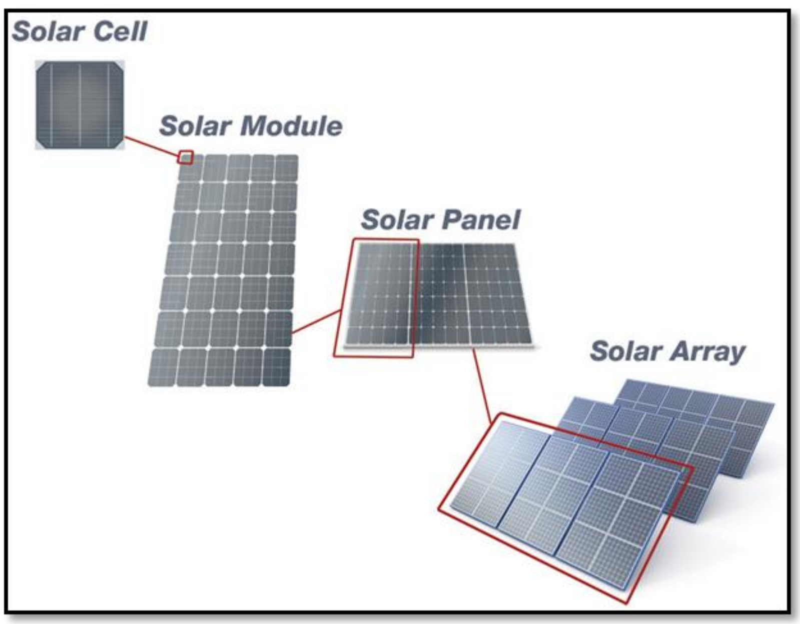


Figure 7: Relationship between solar cells, module, panel and array (Source: www.etap.com, 2015)

The capacity of each solar photovoltaic module is estimated in peak power kilowatts (kWp) or Watts peak (Wp). The peak power capacity refers to the maximum generated electrical power from the solar module if the system is under the standard test conditions

STC (Luque et al., 2003). The standard test conditions STC are as follow (Bergamasco and Asinari, 2011):

- Solar irradiance is at 1000 W/m^2.
- Module temperature is 25 ˚C.
- Air mass is 1.5 (AM1.5). See Figure 8.

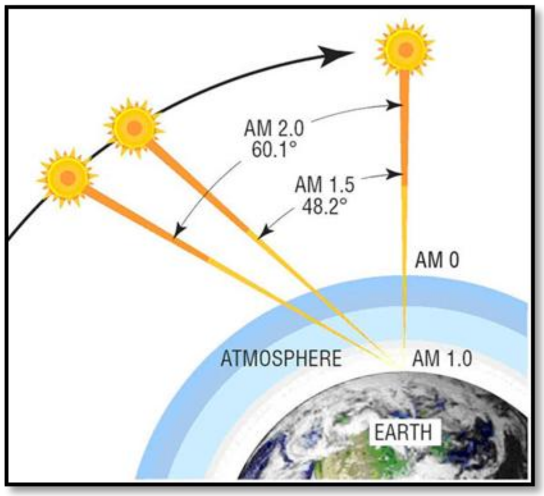


Figure 8: Schematic of atmospheric air mass (pvmeasurements.net)

Usually, the actual generated power from a photovoltaic module is less than its nominal output at STC. And sometimes, it could be greater. In fact, this depends on many factors such as the geographical location, weather status, time during the day, and other reasons.

2.1.2 Types of photovoltaic PV

Photovoltaic systems can be divided into two main types according to its relationship with the electrical grid. Grid connected or on-grid and off-grid systems as shown in Figure 9 and Figure 10. The main difference between on-grid and off-grid is that the first system is usually connected to the public grid or with a separate independent large grid.

The surplus generated electrical power will be fed to that grid when the system is overproducing. On-grid systems are the simplest systems to install and the most cost effective systems. On the other hand, the off-grid systems are designed to store the excess generated energy in batteries to be used later when the system is not producing electricity at the time when there is no sunshine or in bad weather. Nowadays, grid connected PV panels occupy the big portion of global PV market. Whereas, the off-grid systems take smaller portion.

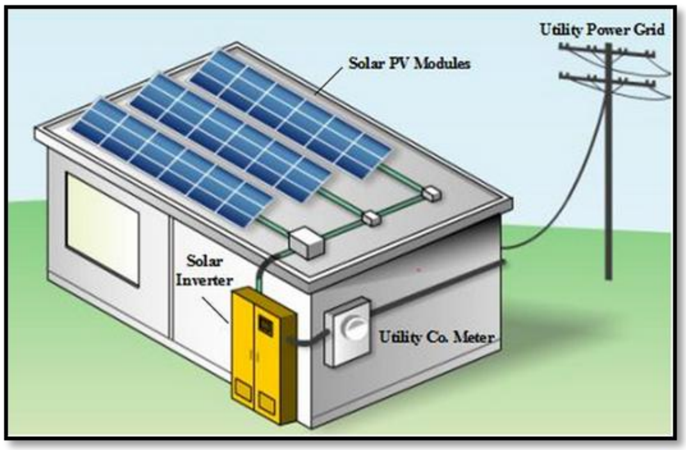


Figure 9: Grid connected photovoltaic system (Midwest Green Energy, LLC)

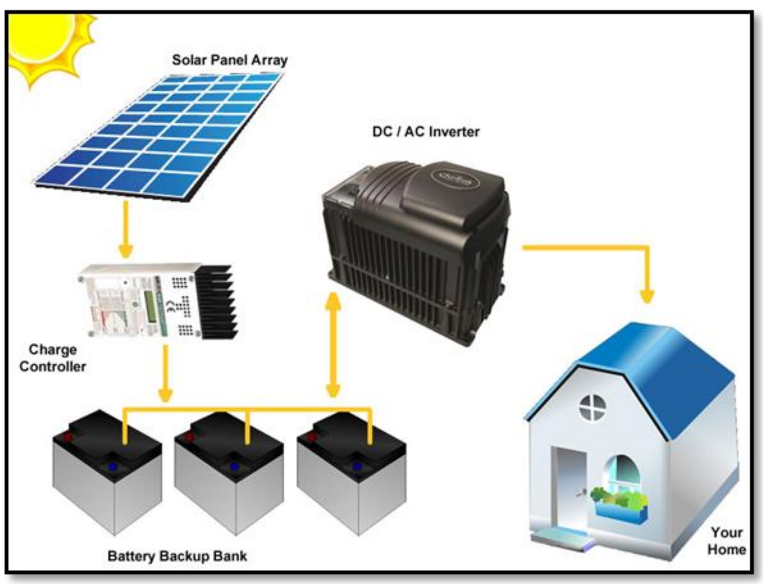


Figure 10: Off-grid photovoltaic system (Silicon Solar Inc.)

Photovoltaic cells can be divided into many categories with respect to their internal composition. The widely known types of solar cells include :

i. Mono-crystalline silicon/ single-crystalline .
ii. Poly-crystalline silicon/ multi-crystalline.
iii. Thin film silicon /Amorphous silicon.
iv. Cadmium telluride (CdTe)
v. Copper indium gallium selenide (CI(G)S)
vi. Gallium arsenide germanium solar cell (GaAs)
vii. Organic solar cell (OPV)
viii. Solid state solar cell

2.1.3 Efficiency of photovoltaic PV

The efficiency of the photovoltaic modules varies with its type. Table 1 shows the efficiency of the three main types of solar photovoltaic modules. It can be noticed that the mono-crystalline silicon cells have the highest efficiency among other types. On the other hand, thin film silicon cells have the lowest efficiency (Midwest Green Energy, LLC).

Table 1: Efficiency of different solar cells

Type of cell	Efficiency
Mono-crystalline silicon	13% - 15%
Poly-crystalline silicon	10% - 13%
Thin film silicon/ Amorphous	5% - 7%

2.1.4 Advantages of photovoltaic PV systems

The advantages of generating electrical power by means of photovoltaic systems can be summarized as (Bazilian et al., 2013):

1. They are quiet with silent operation.
2. They have no engine or mechanical moving parts.
3. They do not have any environmental emissions or poisonous output. Providing clean energy.
4. They do not consume any kind of fuel.
5. Solar energy is free and easily accessible.
6. Require very little maintenance.
7. They look nice with good esthetic appearance.
8. Mature technology. Photovoltaic has being used by more than 50 years by now, and grid-connected by more than 20 years.
9. Prices of the photovoltaic technology becomes cheaper with time as a result of the enormous growth of its market.
10. Solar photovoltaic systems are easy to install.

2.1.5 Disadvantages of photovoltaic PV systems

The disadvantages of generating electrical power by means of photovoltaic systems can be summarized by (Renewable energy world, 2015):

1. Sunshine has issues pertaining intermittency periods. At night, there is no sunshine. In addition, at daytime, if the sky is cloudy or if the weather is rainy.

2. As a result of the above, dependency and reliability on solar panels are not easy, especially when the solar energy is unpredictable.
3. Produces direct current DC. Therefore, it requires extra equipment like inverters to generate usable alternating current AC in the power network.
4. In off-grid systems, it requires the provision of batteries to maintain continuous supply of electricity. Thus, increasing the cost of the system.
5. They need relatively large areas for the implementation of photovoltaic panels. Usually, these panels will stay in place for 15-20 years or longer.
6. The efficiency of solar photovoltaic panels is relatively low 14% - 25% compared with other energy systems.
7. Solar panels are fragile and can be easily damaged.
8. They require periodic cleaning from dust and monitoring.
9. At high temperatures, their efficiency will be reduced.
10. The initial cost of the complete photovoltaic system is relatively high.

2.1.6 Comparison between PV types

Solar photovoltaic cells vary from each other in terms of their efficiency of light conversion, durability, technology, and cost of production. Table 2 provides a comparison between these types (Midwest Green Energy, LLC).

Table 2: Comparison between PV cells

Type of cell	Efficiency	Durability	Technology	Cost of production
Mono-crystalline silicon	13% - 15%	30 years	Oldest	More expensive
Poly-crystalline silicon	10% - 13%	25 years	Relatively new	Lower
Thin film silicon / Amorphous	5% - 7%	20 years	New	Lowest

2.1.7 Applications of photovoltaic PV systems

The most important and promising features pertaining solar photovoltaic technology, that encourage the developers and engineers to adopt and utilize this trend in renewable energy into their designs and projects are:

- Increasing efficiency.
- Trend towards lowering the costs.
- Minimal pollution.

Because of these reasons, photovoltaic solar systems have wide markets and applications in many countries all over the world. Examples of these applications are as follows (Parida et al., 2011):

- Building integrated systems BIPV.
- Desalination plants
- Space applications (satellites and vehicles, etc.)
- Solar home systems

- Pumps
- Power stations
- Photovoltaic and thermal (PVT) collector technology
- Other applications (Communication towers, remote facilities, floatovoltaics, etc.)

It is expected in the light of these vast applications that the photovoltaic market will increase to suit the increasing demand for it (World Energy Council, 2007). Figure 11 shows the cumulative installed capacity of photovoltaic systems in the world (EPIA, global market outlook for photovoltaic 2013-2017).

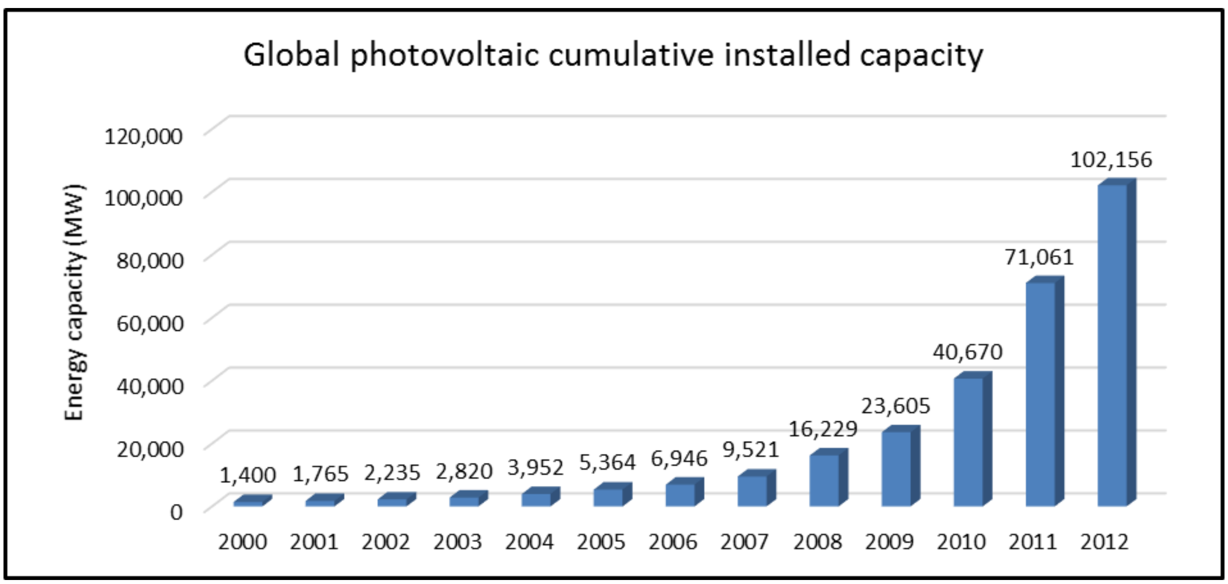


Figure 11: Global photovoltaic cumulative installed capacity

2.2 Feasibility of solar photovoltaic energy in the world

Mutani and Vicentini studied the solar irradiation models present in the literature, applied a 3D model for the study area and the buildings existed on it. They used Digital Surface Model DSM which takes the direction and slope of the terrain into consideration, it also considers the 3D nature of the built up area (Mutani and Vicentini, 2013). They calculated the amount of electrical energy that can be generated from the incident solar irradiation by the photovoltaic technology to be installed on the roofs of residential buildings in the Province of Turin (Italy). By doing so, they evaluated the potential of using integrated PV panels on roofs to reduce or satisfy the residential demand for electricity.

Longo conducted a research in Belem city, Para state (Brazil), aimed to encourage architects, engineers and their clients to adopt the different solutions of solar photovoltaic technologies and building envelopes (Longo, 2013). He showed the advantages of the solar potential in the Amazonia. He researched how to improve the thermal comfort inside the buildings by using the photovoltaic solar systems.

Mandalaki et al. examined the fixed shading systems with PV integrated on them in Mediterranean countries. They evaluated those shadings according to their ability to save energy and maintain good visual comfort (Mandalaki et al., 2013). It was concluded that they could achieve these goals except that they cannot provide enough daylight away of the window, and thus affecting the conditions for comfortable daylight.

Montero et al. explained the concept of building integrated photovoltaics BIPV. (Montero et al., 2013) Defined it as a single element that combines features such as electricity generation, solar control, thermal insulation, and architectural design.

It is very important when attempting to develop energy policies to make an assessment of the potential of renewable energies (Izquierdo et al., 2008). Izquierdo et al. studied the technical potential of roof-integrated photovoltaic systems. They proposed a hierarchical methodology to estimate the roof available areas within a given region, taking into account the errors that might occur during the process. Their work depended basically on GIS maps. Their methodology can be applicable for regional to continental scales with obtained confidence level of 95%.

A methodology to estimate the potential of roof-top photovoltaic using satellite images and GIS for a micro-scale level was developed by Singh and Banerjee. They collected the images from satellites using Google Earth. Categorization and nomenclature were done to the images. Then, they were georeferenced with the help of QGIS software (Singh and Banerjee, 2013). After that, the total roof areas and the utilizable areas were calculated. Finally, simulations were carried out to estimate the energy generation potential using PVsyst software.

The factors that influence the electricity generation of the rooftop photovoltaic system were analyzed by Hong et al. These factors can be summarized as regional factors and on-site installation methods (Hong et al., 2013). The regional factors include both geographic and meteorological information. The geographic information can be expressed by latitude and sun meridian altitude. Whereas the meteorological information consists of monthly solar radiation and average temperature. On-site installation has information about azimuth and slope of the panels, type of invertor and panels. Finally, they proposed a GIS-based model after optimizing the aforementioned factors for South Korea. This model helps in estimating the amount of electricity that could be generated by using PV systems.

A methodology to assess the potential of the solar PV energy was presented by Bergamasco and Asinari. They proposed a hierarchical procedure to evaluate the solar radiation, estimate the available roof areas for BIPV systems and their performance (Bergamasco and Asinari, 2011). GIS data was analyzed to calculate the suitable roof areas for PVs. This methodology was applied to Piedmont, Italy.

Hofierka and Kanuk conducted a study for estimating the potential of photovoltaic in urban areas. They proposed a methodology to assess that potential. (Hofierka and Kanuk, 2009) Benefited from an open-source tool for solar radiation and from a three-dimension city model, which was implemented in GIS (r.sun solar radiation model and PVGIS estimator). The study was carried out in eastern Slovakia in a small city. After the analysis was done, they came up with interesting results. Almost 2/3 of the electricity consumed in the city can be covered by adopting PV systems.

Usually, the growth of megacities is accompanied with increasing energy demand issues. Kabir et al. studied the potential of generating electrical energy through solar PV system in megacities. To do so, they took Dhaka Megacity in Bangladesh as a case study. And calculated the areas of the bright roof-tops of the buildings. Utilizing imagery analysis techniques from Quickbird Scene (Kabir et al., 2009). They managed to estimate the potential of power generation for PVs. It was found that applying 75Wp standalone PV system modules would generate 1000MW. This amount of electrical energy will meet the power demand of the city.

A methodology to determine the potential of solar energy for on-grid PV systems was proposed by Ordonez et al. for Andalusia (Spain), which has the highest solar radiation potential among Europe. They only considered the residential rooftops area for the PV systems. The proposed methodology comprised of describing building characteristics, calculation of advantageous rooftop areas where the PV arrays could be assembled, and estimating the electrical energy generated by solar panels (Ordonez et al., 2010). They found that almost 78% of energy demand in Andalusia could be recovered if the PV systems would be used as a renewable power supply.

Wiginton et al. demonstrated a methodology for determining the useful rooftop areas for the deployment of photovoltaic systems in large-scale regions in Ontario, Canada. They benefited from merging the capabilities of object-specific image recognition with geographic information systems GIS (Wiginton et al., 2012). The potential of solar PV systems was estimated. It was found that 30% of the energy consumed in Ontario could be generated from rooftop PV systems installed at a province-wide scale.

The feasibility of a city-scale building integrated PV application was studied in Arizona by Jo and Otanicar. Object oriented image analysis and GIS were combined with remote sensing image data, for estimating the available rooftop areas for solar photovoltaic systems (Jo and Otanicar, 2011). RETScreen software was used to predict the potential of energy generation. Environmental benefits were also discussed and estimated.

The performance potential of photovoltaic systems was evaluated by Strzalka et al. in urban areas near Stuttgart, Germany. They used a 3D geometry model technology which includes shading algorithms for that purpose (Strzalka et al., 2012). Simulations for energy potential were carried out using INSEL8 software. A comparison with the measured energy consumption was done to get the own consumption rations in these urban areas.

Parida et al. reviewed the photovoltaic technology, its capabilities of power generation, hybrid photovoltaic systems, and light absorbing materials being used in PV systems (Parida et al., 2011). They also discussed photovoltaic technology in terms of its applications and environmental aspects.

A techno-economic feasibility study was conducted by Bakos et al. for grid-connected photovoltaic system, integrated with buildings' rooftops in Kastoria, north Greece. Economical and technical factors were taken into consideration with different scenarios (Bakos et al., 2002). RETScreen computer software was used as an assessment tool. They estimated the gross return of the investment and concluded with the encouragement for adopting such kind of renewable energy sources.

Adoption of solar photovoltaic technology in buildings was assessed in terms of energy and economic evaluation by Oliver and Jackson. They established a comparison between solar PVs and both to centralized PV plants and conventional sources (Oliver and Jackson, 1999). The cost of PVs is higher than conventional resources. However, in terms of environmental potential, PVs show higher environmental performance. Whereas, BIPV reflects lower economic costs and higher environmental performance rather than normal solar PV systems.

A methodology was developed by Muselli et al. to estimate the potential of various renewable energy systems. The proposed methodology utilized geographic information system GIS technology to find out the optimal energy generation choice out of four suggested choices depending on the least cost of energy generation (Muselli et al., 1999). They came up with a conclusion that the most economical choice for electrification in 60-90% of remote sites in Corsica, France is a PV decentralized systems.

Gagliano et al. benefited from GIS capabilities for determining the rooftop areas suitable for photovoltaic systems installation in an urban area in San Cataldo, Italy (Gagliano et al., 2013). They produced thematic maps of photovoltaic energy generation. These maps are very powerful tools for planning renewable energy sources.

2.3 Feasibility of solar photovoltaic energy in Saudi Arabia

2.3.1 Solar irradiance and solar irradiation

When studying solar systems there are two specific terms that one must differentiate between them, solar irradiance and solar irradiation. Solar irradiance indicates the power or the instantaneous solar energy acting on unit area per unit of time, and is measured in (W/m^2). On the other hand, solar irradiation refers to solar energy, and can be defined as the solar energy acting on unit area over a specific time period, usually it is measured in (Wh/ m^2).

2.3.2 Factors affecting solar radiation

The amount of solar radiation reaching the earth and specially the photovoltaic panels is affected by many factors. Many researchers studied these factors and its influence on the incident solar radiation obtained (Suri and Hofierka, 2004). These factors are represented as follow:

1. Geometry of Earth, rotation, declination, and latitude.
2. Terrain geometry (i.e. elevation, shadow, surface orientation and inclination).
3. Atmospheric attenuation represented by scattering and absorption occurred by air gases and molecules, suspended solid particles, and clouds.

2.3.3 Solar radiation in Saudi Arabia

Saudi Arabia is relatively considered as a large country in the Middle East region. With a total land area of 2,149,690 km^2. It is situated between 17.5˚N and 31˚N in latitude, and 36.5˚E to 50 ˚E in longitudes. It is granted with relatively high potential of both solar radiation and sunshine hours as a result of its unique location and climate, see Figure 12. It can be noticed from Figure 13 which shows the direct normal irradiation for Africa and Middle East regions, that KSA has a good range of 1800 – 2400 (KWh/m^2) average annual of solar irradiation. Rehman et al. 2006 reported in his study about solar photovoltaic in KSA, that the kingdom has 40 stations working since 1970 to record the solar radiation and meteorological data.

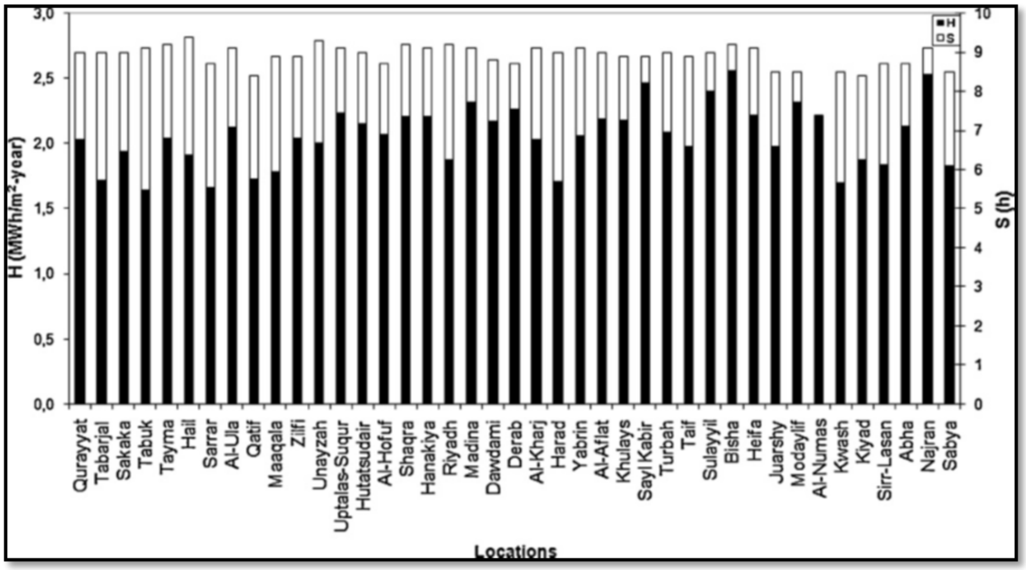


Figure 12: Solar radiation (H) and sunshine duration for several locations in KSA (Hepbasli and Alsuhaibani, 2011)

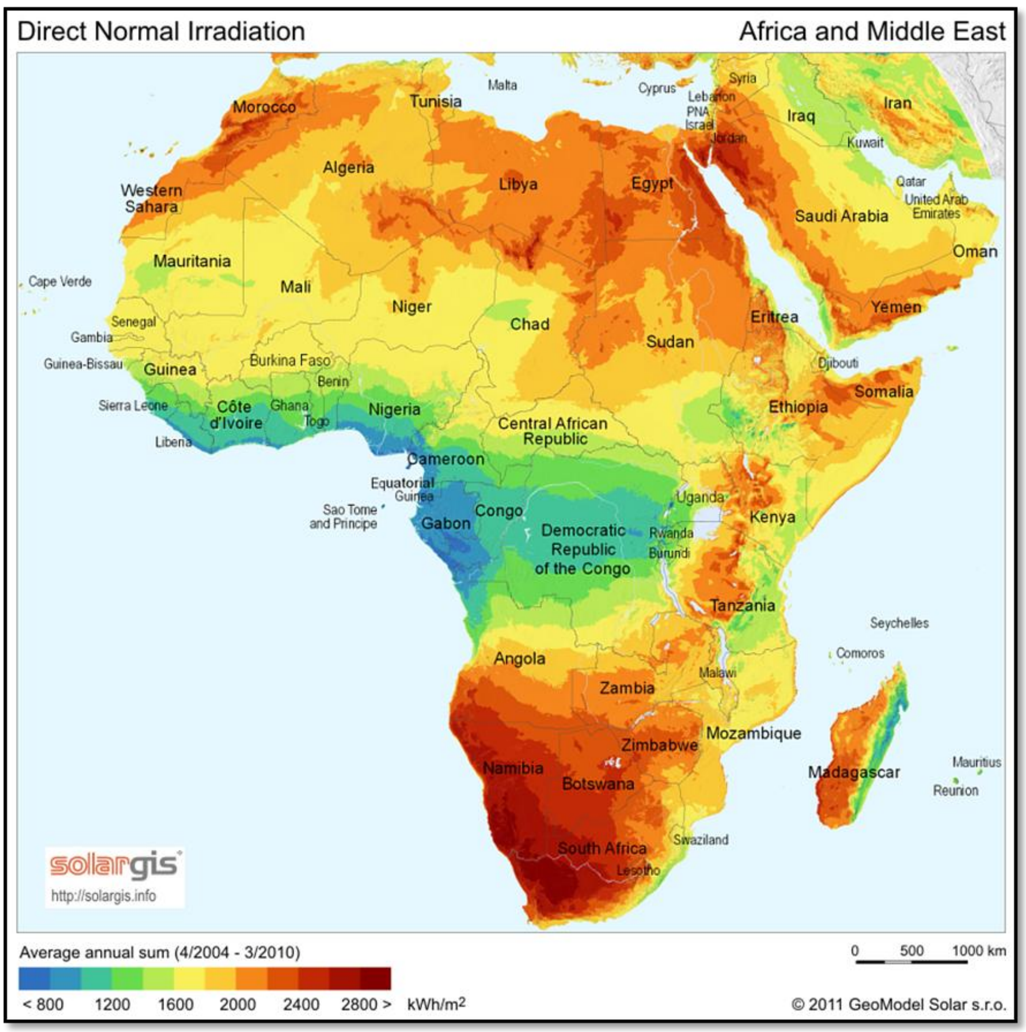


Figure 13: Direct Normal Irradiation for Africa and Middle East (SolarGIS)

This study will be conducted in KFUPM campus located in Dhahran area, Eastern Province - Saudi Arabia for the purpose of the research. Dhahran area as shown in Figure 14 has around 1800 (KWh/m^2) average annual of solar irradiation.

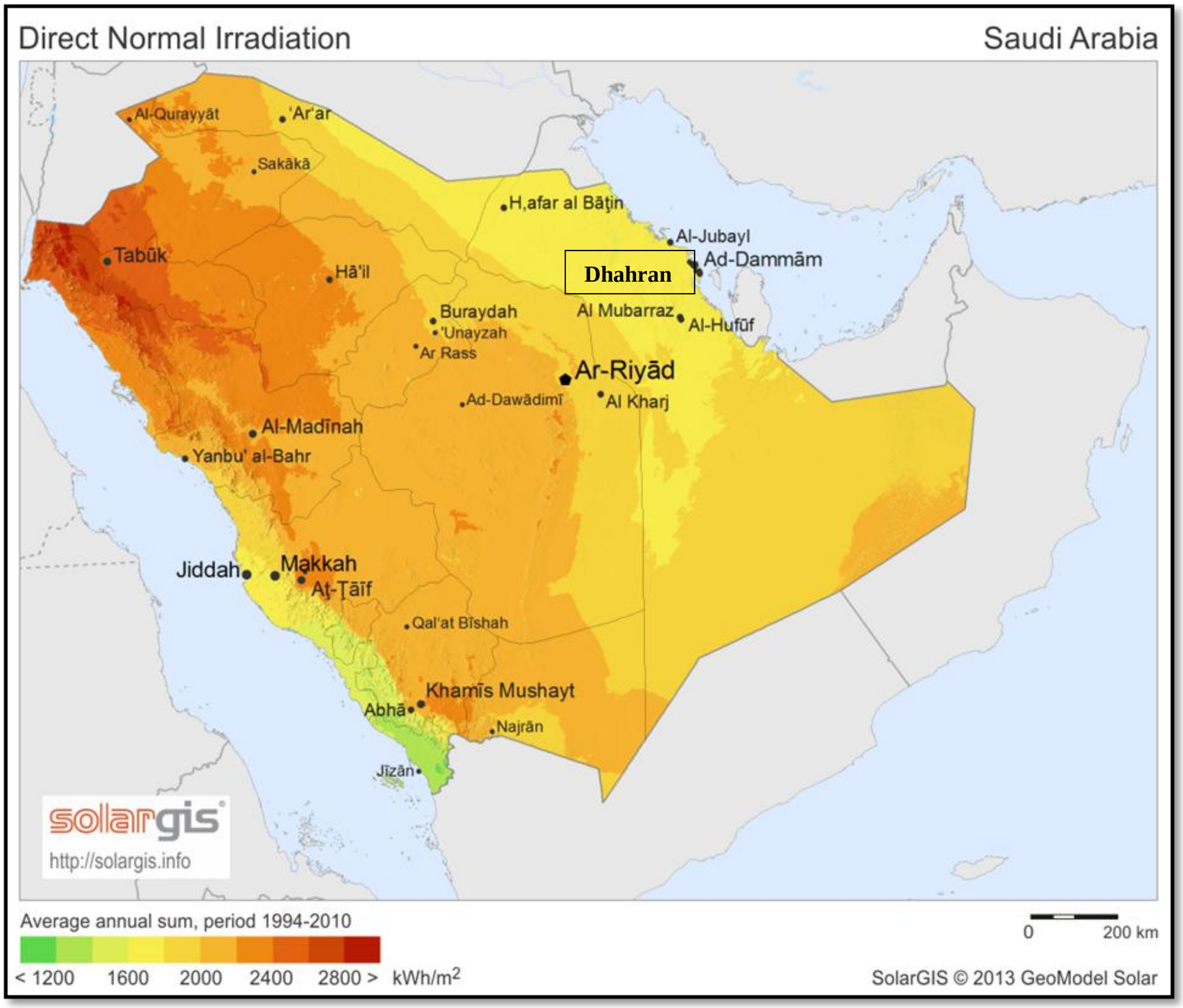


Figure 14: Direct Normal Irradiation in KSA (SolarGIS)

The incident solar radiation over Saudi Arabia is changing with season change. Figure 15 clarifies this seasonal change.

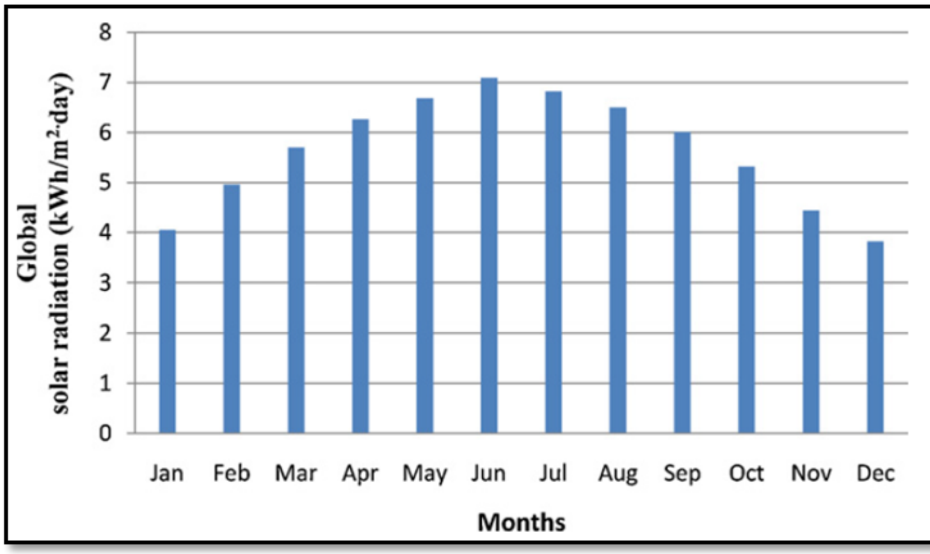


Figure 15: Seasonal change of solar radiation in KSA (Hepbasli and Alsuhaibani, 2011)

2.3.4 Relevant studies of solar PV potential in KSA

A feasibility study for generating electricity from PV panels in Saudi Arabia was conducted by Rehman et al. They took 41 regions in KSA. Studied the solar radiation and sunshine duration over these areas (Rehman et al., 2006). Then, the energy potential generated in each area was obtained using RETScreen software. Moreover, these PV systems were economically analyzed to discover their feasibility. Finally, an environmental assessment was carried out to find how much greenhouse gases would be prohibited from being released to the atmosphere of KSA, if these PV panels were applied. It was found that Al-Bisha region in KSA is the best region over the 41 region been studied.

They also indicated that seasonal change of solar radiation in KSA tunes with the demand of electrical load profile, which will has a peak demand on summer season. Figure 15 and Figure 16 makes it easy to comprehend the relationship.

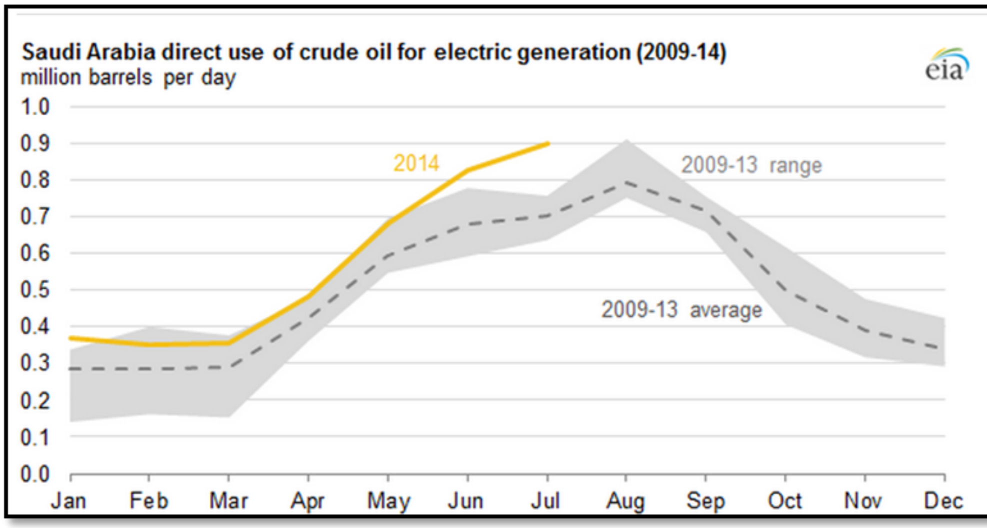


Figure 16: Crude oil demand for electricity generation in KSA (Energy Information Administration, 2014)

Other study by Almasoud and Gandayh who made a comparison between the cost of energy of solar PV and conventional fossil fuel in Saudi Arabia (Almasoud and Gandayh, 2014). It was proved that solar PV energy implies less cost when compared with conventional sources of energy in KSA, if the damage costs to the environment and public health sectors are taken into consideration.

In lights of the relevant studies of solar PV potential in KSA, this study could be considered as a contribution because of the following reasons:

- It has a whole campus scale. All KFUPM buildings are taken into consideration. The campus is huge in size and has high power generation capabilities.
- Using rooftop PV systems instead of stand-alone arrays on the ground.
- The challenge in finding out the percentage of rooftop utilizable areas for PV panels.

- Implies energy generation optimization process between applying PV panels on the buildings' rooftop in two cases: tilted with the optimal inclination angle, and horizontal with zero inclination.
- Has a detailed cost analysis of the initial investment, maintenance and operational costs, system parts replacements costs, annual costs benefits of the generated energy.

2.3.5 Interest in solar energy in Saudi Arabia

Interest towards utilizing solar energy applications in Saudi Arabia has been expanding since 1960. A systematic research for developing solar energy technologies in Saudi Arabia was initiated by King Abdul-Aziz City for Science and Technology (KACST) in 1977.

A research project between KACST and the US National Renewable Energy Laboratory established the Solar Radiation Atlas for Saudi Arabia (Almasoud and Gandayh, 2014).

The Ministry of Higher Education MOHE founded a Center of Research Excellence in Renewable Energy at the King Fahd University of Petroleum and Minerals KFUPM in 2007. This center aims at developing renewable energy technologies, especially solar energy.

Rehman, 2010 in his study described the annually installed capacity of solar photovoltaic and the cumulative capacities for each year during the period 2002 to 2008 in the Kingdom of Saudi Arabia in Figure 17.

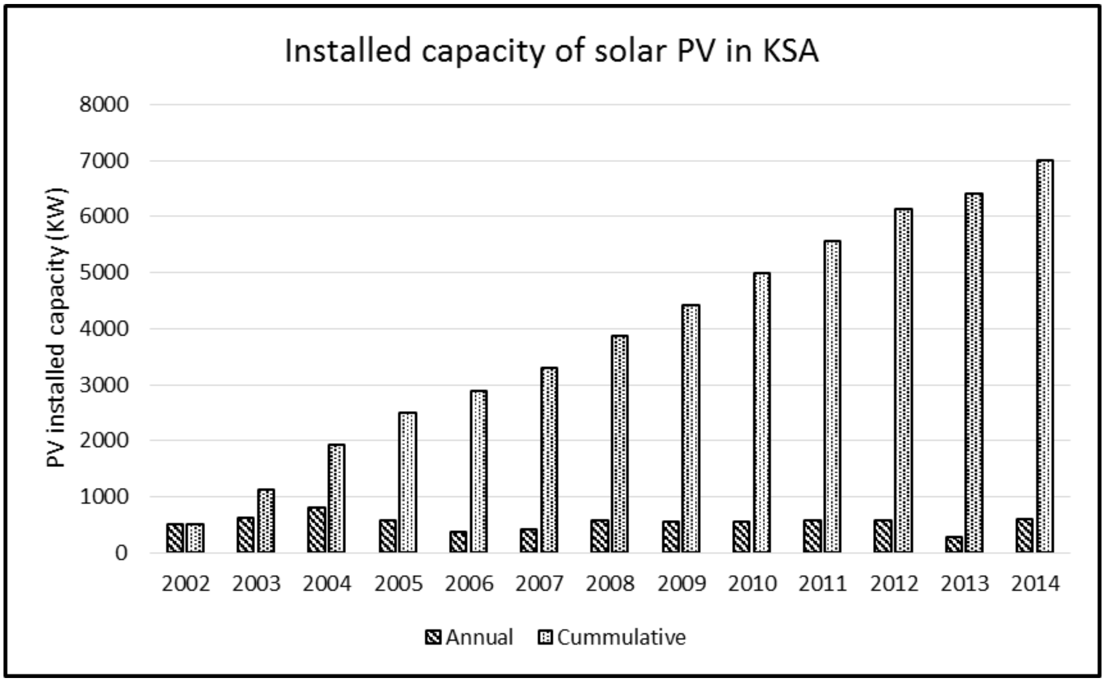


Figure 17: Annually installed capacity of solar PV and the cumulative capacities in KSA (Source: Author and Rehman, 2010)

Many major research and development R&D projects were established in Saudi Arabia over the past years. Table 3 shows a brief description for these R&D projects (Almasoud and Gandayh, 2014; Alawaji, 2001; Huraib, 1996).

The energy research institute (ERI) in KACST has been conducting research projects pertaining solar energy utilization in Saudi Arabia. Table 4 clarifies these projects in details.

Table 3: Research and Development (R&D) projects in Saudi Arabia

Project name	Brief description	Capacity	Generated Energy
The solar village project	Located in Riyadh. Generate electricity to supply remote villages that are not connected to national grid. Started in 1980.	350 kW	1-1.5 MWh/day
Solar Thermal Dish Project	Started in 1982. Is a joint program between KACST and the Federal Ministry of Research and Technology, Germany. Aimed at producing electricity from thermal dishes.	100kW	NA
Solar-Powered Water Desalination Projects	Established at Yanbu in 1984. A seawater desalination pilot plant. Uses dual axis sun-tracking collectors. Produces 200 m^3 of potable water each day. Closed for economic reasons.	11 kWp	NA
PV-Powered Water Pumping	Founded in 1994 at Riyadh. Provide electricity for water pumps used to bring up underground water to the surface.	NA	NA
Solar Radiation Resources and Assessment Projects	The Saudi Atlas Project started in 1994. Offers exact measurements of solar radiation in Saudi Arabia.	NA	NA
350KW Solar Hydrogen Production Project	The plant is located in the solar village project in Riyadh. Produces hydrogen through PV technology. 463 m^3 of hydrogen in generated each day.	350 kW	NA
Solar-Powered Highway Devices Project	Installing lighting systems for two remote tunnels in the southern mountains of KSA. 1.5 MWh of electrical energy is produced each day.	NA	1.5 MWh/day
Photovoltaic Research Project	Located in the solar village project, Riyadh. Aims to evaluate the performance of PV cells with directional variation, temperature, dust, and rotation.	3 kW and 6 kW	NA
Solar Dryers	To develop an efficient solar dryer for drying dates. It was tested in Al-Hassa and Qatif agricultural experimental sites.	NA	NA

Solar Water Heating Project	Energy Research Institute ERI in Saudi Arabia conducted several studies for the development of solar water heating systems.	1100 solar flat plat collectors	NA
2MW PV cells at KAUST	Started in 2010. Located in Jeddah. Producing 3300 MWh annually.	2 MW	3300 MW/year
The Farasan Solar Power Plant	Initiated in 2011. Uses standalone PV systems. Feeding Farasan Island with electricity.	NA	NA
The North Park Project	Situated in Dhahran at the headquarters of Saudi Aramco oil company. The largest solar parking project in the world. Covers 200,000m^2 and has 10MW system. Started working in 2011.	10 MW	NA

Table 4: Research projects carried out by ERI, KACST for solar energy in KSA (Alawaji, 2001; Rehman, 2006; Hepbasli, 2011)

Period or year conducted	Location	Description of projects		Application purposes
		Type	Capacity	
1981–1987	Solar Village	PV system	350 kW (2155 MWh)	AC/DC electricity for remote areas
1981–1987	Saudi universities	Solar cooling	–	Developing of solar cooling laboratory
1986–1991	KAU, Jeddah	Solar hydrogen	2 kW (50 kWh)	Testing of different electrode materials for solar hydrogen plant
1986–1994	Solar Village	Solar-thermal dishes	2 pieces, 50 kW	Advanced solar stirling engine
1987–1990	Solar Village	PV test system	3 kW	Demonstration of climatic effects
1987–1993	Solar Village	PV hydrogen production	350 kW (1.6 MWh)	Demonstration plant for solar plant hydrogen production
1988–1993	Dammam	Energy management in buildings	–	Energy conservation
1988–1993	Al-Hassa, Qatif	Solar dryers	–	Food dryers (dates, vegetables, etc.)
1989–1993	Solar Village	Solar hydrogen generator	1 kW (20–30 kWh)	Hydrogen production, testing and measurement (laboratory scale)
Since 1990	Solar Village	Long-term performance of PV	3 kW	Performance evaluation
1993–1995	Solar Village	Internal combustion engine	–	Hydrogen utilization
1993–1997	Solar Village	Solar collectors development	–	Domestic, industrial, agricultural
1993–2000	Solar Village	Fuel cell development	100–1000 W	Hydrogen utilization
1994–1999	Sadous Village	PV water desalination	$0.6\ m^3$	PV/RO interface per hour
1994–2000	12 stations	Solar radiation measurement	–	Saudi solar atlas
1994–2000	5 stations	Wind energy measurement	–	Saudi solar atlas
1996	Southern regions of Saudi Arabia	PV system	4 kW	AC/DC electricity for remote areas
1996	Muzahmia	PV in agriculture	4 kWp	AC/DC grid connected
1996–1997	Solar Village	Solar-thermal desalination	–	Solar distillation of brackish water
1996–1998	Solar Village	PV system	6 kW	PV grid connection
1999–2000	Solar Village	Solar refrigeration	–	Desert application

2.3.6 Economic feasibility analysis

2.3.6.1 Definition

The analytical process through which the principal purpose is to investigate the economic indicators of a firm or project is called economic feasibility analysis. These indicators are mainly represented by the economic benefits and costs pertaining to a project or an organization. A project would be economically successful, if it has positive economic indicators, or in other words positive benefits. The assessment process usually employs benefit to cost ratio BCR analysis (Georgakellos and Marcis, 2009). The feasibility analysis helps the decisions maker to better compromise and select the best alternative.

2.3.6.2 Economic parameters

The main purpose of the economic feasibility analysis is to help the decision maker to properly decide upon his project alternatives. Economic parameters are very critical when attempting to investigate the economic viability of a new project. There are many economic indicators or parameters that can be used in this issue. The most common parameters that would help in the decision making process are (Justis and Kreigsmann, 1979) and (Thompson and Wright, 1985):

1) Total cost of the project.
2) Financing policy of the project (initial costs, running and operational costs, and maintenance cost).
3) Expected cash flow of the project and profitability.

4) Net present value, NPV.

5) Internal rate of return, IRR.

6) Benefit to cost ratio (or profit to investment ratio).

In finance, the net present value NPV can be defined as "the sum of the present values of incoming and outgoing cash flows over a period of time" (Berk et al., 2015). The net present value of a project can be used in decision making according to its value as follows:

- If the NPV is positive. Then, the investment would add value to the project, and the project may be approved.
- If the NPV is negative. Then, the investment would deduct value from the project, and the project may be discarded.
- If the NPV is zero. Then, the investment would neither add nor deduct value form the project. Decision making process shall be based on other criteria.

The Internal rate of return IRR is the interest rate which makes the net present value of a project's cash flows is equal to zero. Usually, if the internal rate of return of a project is greater than its interest rate, then the project would be beneficial.

The benefit to cost ratio BCR will be explained in the following subtitle.

2.3.6.3 Benefit to cost ratio

Benefit to cost ratio is considered as an economic indicator, used by the economic analyst to summarize the total monetary value of a proposed project during its cost-benefit analysis phase. BCR is simply the ratio between the benefits and costs of a proposed project, provided their monetary values.

$$Benifit\ to\ cost\ ratio\ BCR = \frac{Benefit - Losses}{Cost}$$

If the project does not have losses (dis-benefits), then the ratio becomes:

$$Benifit\ to\ cost\ ratio\ BCR = \frac{Benefit}{Cost}$$

The principal concept of BCR is that it integrates the monetary values of the project’s gained benefits with its execution costs. The higher the benefit to cost ratio the more beneficial is the project, and consequently, the better the investment.

2.3.6.4 Economic feasibility using computer software

Rehman et al., 2006 conducted an economic feasibility study for a 5MW photovoltaic power plant research in KSA using RETScreen software. This computer software performs the economic feasibility for most types of renewable energy systems. It takes the following economic indicators into consideration:

- Internal rate of return, IRR.
- Simple payback period, SPP.
- Years to positive cash flow, YPCF.
- Net present value, NPV.
- Annual life cycle savings, ALCS.
- Profitability index, PI.

Table 5 shows the most important input parameters that were used in the photovoltaic economic feasibility analysis in Saudi Arabia.

Table 5: Economic parameters used in photovoltaic economic feasibility analysis in KSA (Rehman, 2006)

Economic indicator	Value
Inflation rate	2%
Discount rate for inverters replacement	4%
Project life	25 year

If the internal rate of return is equal to or greater than the desired rate of return, then the photovoltaic project is acceptable. This can be done by calculating the discount rate making the project's NPV is equal to zero.

RETScreen also finds out the number of years required for the project to take back its initial cost, referred to by SPP. The software takes the total initial and annual costs, and it considers the annual savings for that purpose. Then, it calculates the number of years required to positive cash flow YPCF.

In net present value analysis NPV, all the cash inflows and outflows of the investment are converted to their present values. Then, the net value is calculated. If the NPV is positive, this is and indicator that the investment project is feasible (Bakos et al., 2002).

2.4 Obstacles

The number of solar photovoltaic systems applications and markets are following increasing trend. However, there are challenges and obstacles that may delay that expansion. Some of these obstacles in Saudi Arabia are:

1) For rooftop solar PV, the interference with other building systems such like the structural, architectural and mechanical systems (Jo and Otanicar, 2011):
   - Skylights
   - HVAC and plumbing vents
   - Chimneys
   - Overhead tanks

   These kinds of obstructions have different effects on solar photovoltaic according to their height and size.

2) Oil is available at low cost in Saudi Arabia.
3) Temperature and dust effect. Saudi Arabia has hot weather most of the year. The increase of the photovoltaic panels' temperature is very likely to occur due to the hot ambient air and because of the direct sunrays heating the panels. The output efficiency of the panels is inversely proportional with their temperature. On the other hand, the dust accumulation on the panels resulting from dusty weather will also decrease their efficiency, because the dust particles will block some solar radiation from entering the solar cells to be converted to electricity (Adinoyi and Said, 2013).
4) The government of Saudi Arabia subsidies oil and thus electricity generation. But does not subsidy the electricity generation from renewable energy sources (solar photovoltaic as an example). This policy will make it difficult to shift to solar programs which have to compete with commercial sources of energy (Alawaji, 2001).

2.5 Discussion

This chapter provides the reader with all the necessary information about the solar photovoltaic systems. It starts with the basic definitions of photovoltaics, types and efficiencies. Supported with comparisons between PV solar cells types, advantages and disadvantages of PV systems. Then, enumerates its wide range of applications.

The chapter also addresses many research studies that were conducted about the feasibility of solar photovoltaic energy utilization in the world. Starting with researches identifying the potential of solar irradiation, building integrated photovoltaic, and methods to estimate the available roof top areas. These researches vary in size, from regional to continental scales. Most of them were techno-economic assessments of the potential of roof top photovoltaic systems using satellite imagery technology and geographic information system (GIS).

Then, the chapter discusses in details the feasibility of solar photovoltaic energy in Saudi Arabia. The solar radiation in KSA was studied and estimated from the available solar maps and previous studies. Following to this, is an investigation in the literature, particularly for relevant studies of solar PV potential in KSA. It also reflects the interests in solar energy in Saudi Arabia represented by both research and development projects (R&D). Finally, the photovoltaic economic feasibility was discussed in terms of its definition, economic parameters, benefit to cost ratio analysis, and using RETScreen software in the economic analysis for renewable energy sources utilization. The chapter ends with the possible obstacles and barriers that could affect or delay the increasing expansion of utilizing solar energy in the world and Saudi Arabia.

A roof top solar photovoltaic system is composed of many solar panels installed on the roofs of buildings, see Figure 18. The panels in turn convert the solar energy to electrical energy. These systems could be either grid-connected or off-grid systems. The off-grid systems use batteries to store the generated electricity to be used when it is required later. Whereas, the grid-connected systems directly inject the surplus electricity to the grid, usually at a price higher than what the grid feeds the consumer. That price is known as Feed-in Tariff (FIT).

The mentioned technology of utilizing the solar energy by means of photovoltaic is highly successful in many countries around the world. This research comes to study the potential of roof top photovoltaic system in Saudi Arabia. As it has ample of solar radiation and sunshine hours in most seasons in the year.

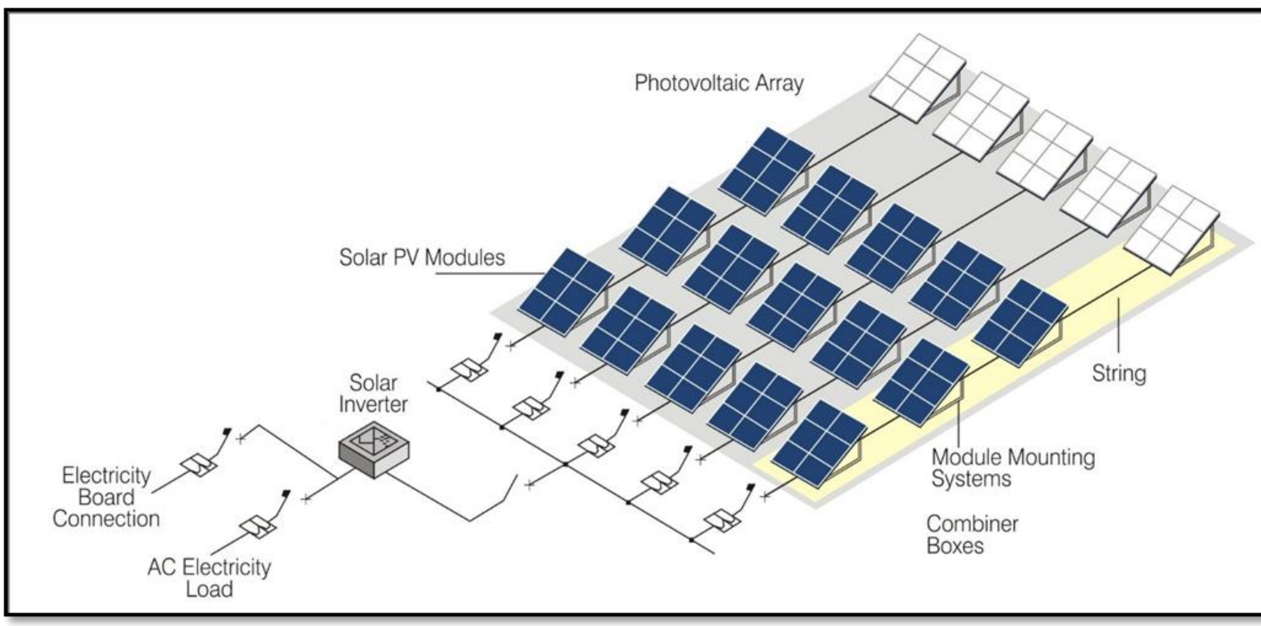


Figure 18: Schematic diagram for solar PV panels (Mid West Green Energy)

It is worth mentioning that this study is distinct as it takes the rooftops of KFUPM buildings as a real case study from Saudi Arabia. Offering a methodology to find the available roof top areas for PV panels installation. In addition, making optimization for energy generation from both flat and tilted implementation of solar PV panels. Then, conducting economic feasibility study based on benefit to cost ratio analysis. Finally, estimating the environmental GHG emissions that would be prohibited from being released to the atmosphere by utilizing the solar PV panels. It has not been found in the literature such a similar study in Saudi Arabia taking all of these cases at the same time.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction

As discussed in Chapter1, this study aims at investigating the feasibility of solar photovoltaic systems installed on the buildings' roof tops in King Fahd University of Petroleum and Minerals KFUPM. The research will concentrate on the incident solar energy on buildings' roof top, electrical energy that could be generated from solar panels (photovoltaic), and on the economic and environmental benefits that could be achieved as a result of the generated energy.

3.2 Research methodology

In order to accomplish the study objectives, a research methodology is set consisting of the following phases:

1) A comprehensive literature review has been conducted to address the main issues regarding solar photovoltaic (benefits and advantages, challenges, costs, etc.).
2) Evaluation of solar energy on the available roof top areas using weather data from various sources (software integrated data or SolarGIS maps).
3) Determination of roof top utilizable areas in academic and non-academic buildings in KFUPM employing GIS (geographic information system) and satellite imagery techniques.
4) Design and optimization of roof top solar PV systems, taking into account solar PV orientation and inclination, also seeking help from PVsyst and RETScreen software.

5) Benefit-cost analysis of the designed PV system considering appropriate economic indicators.

6) Calculation of environmental benefits by estimating associated GHG reduction.

The overall research methodology flow chart is shown in Figure 19 .

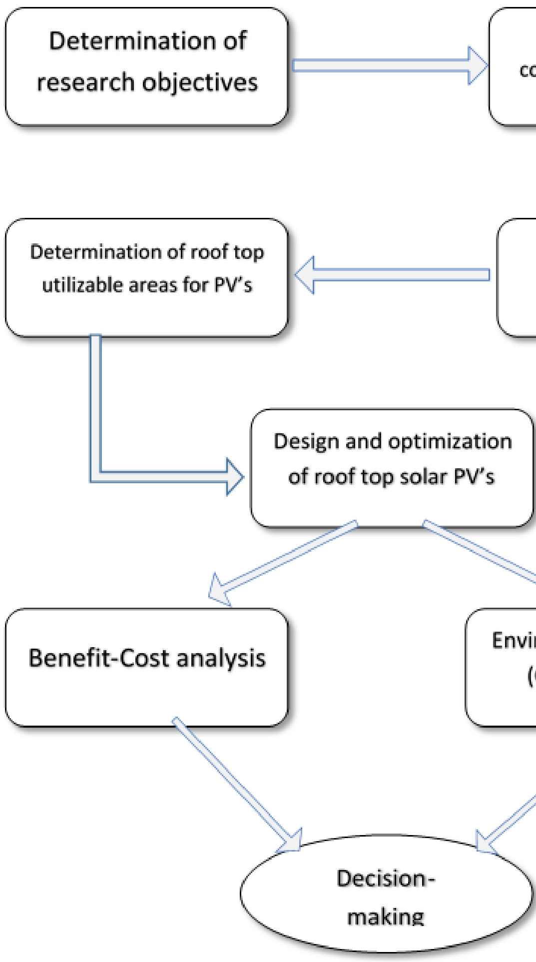


Figure 19: The overall research methodology flow chart

3.2.1 Literature review

A comprehensive literature review was done. Figure 20 shows the detailed flow chart of it. During the literature review phase, all the basic information pertaining to the solar photovoltaic systems, starting from its definition, types, efficiency, advantages and disadvantages, comparisons between PV types, and its major applications. Then, the feasibility of the solar PV in the world was studied. After that, the feasibility of solar PV in Saudi Arabia was investigated. The solar radiation potential and the factors affecting it were studied with the help of relevant studies conducted in Saudi Arabia. Then, the interest of solar PV technology in KSA was identified thought the solar PV projects, which were carried out in Saudi Arabia. The economic feasibility was also studied through its definition, economic parameters, and benefit to cost analysis.

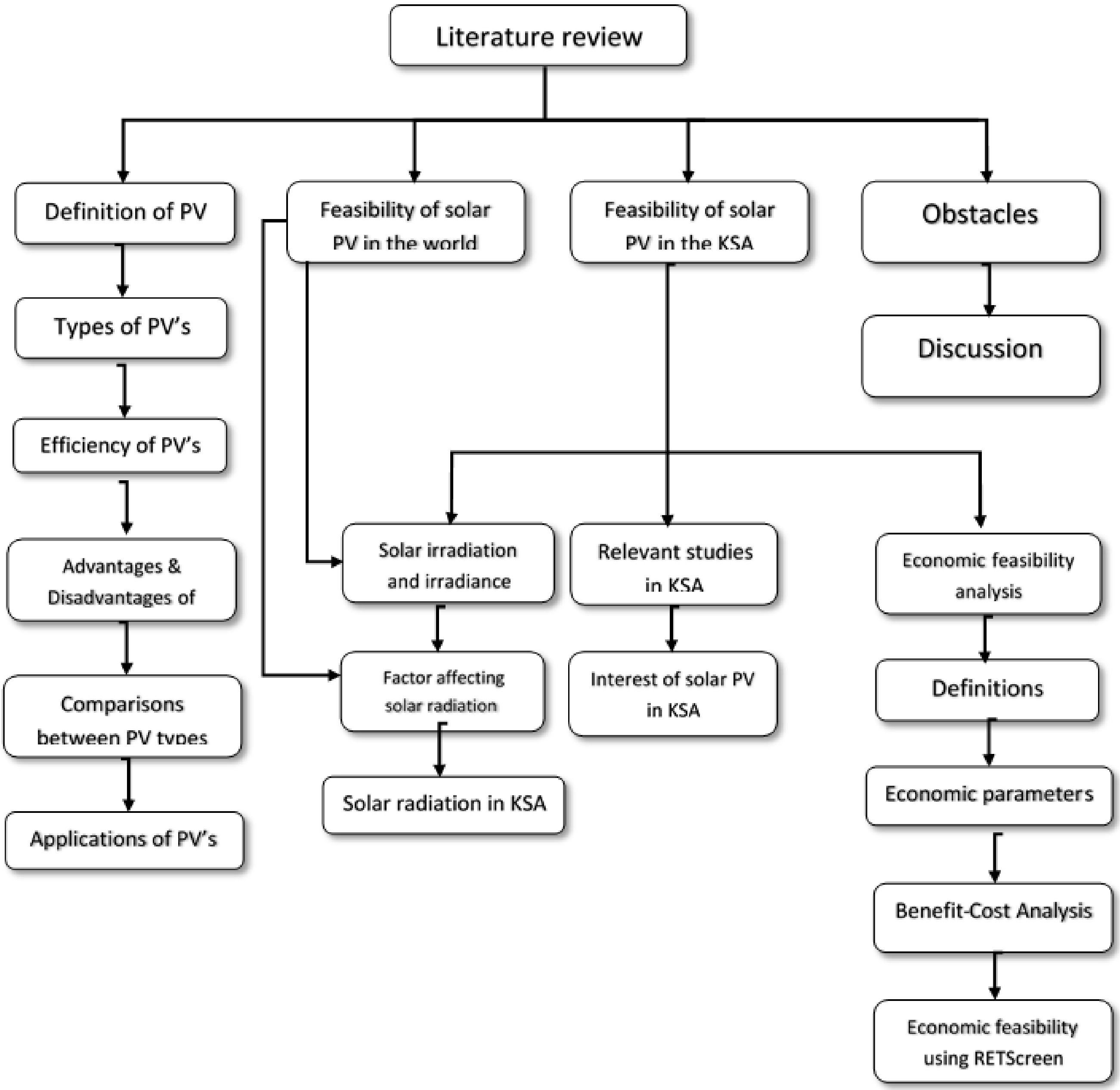


Figure 20: Detailed flow chart of literature review

3.2.2 Assessment of roof top solar potential

The assessment of roof top solar potential can be achieved through the following steps. Figure 21 shows the flow chart of this assessment in details.

- Determining the available incident solar energy on KFUPM, Dhahran area, Saudi Arabia, from the global solar maps /weather data records.

- Gathering the total buildings' roof top areas from the available GIS databases in KFUPM.

- Finding out the total roof top available areas that can be utilized to apply solar photovoltaic systems on it (utilizable areas). This means the total roof top areas excluding the areas that could not be utilized (i.e. areas occupied by HVAC systems, service, and skylight areas, etc.).

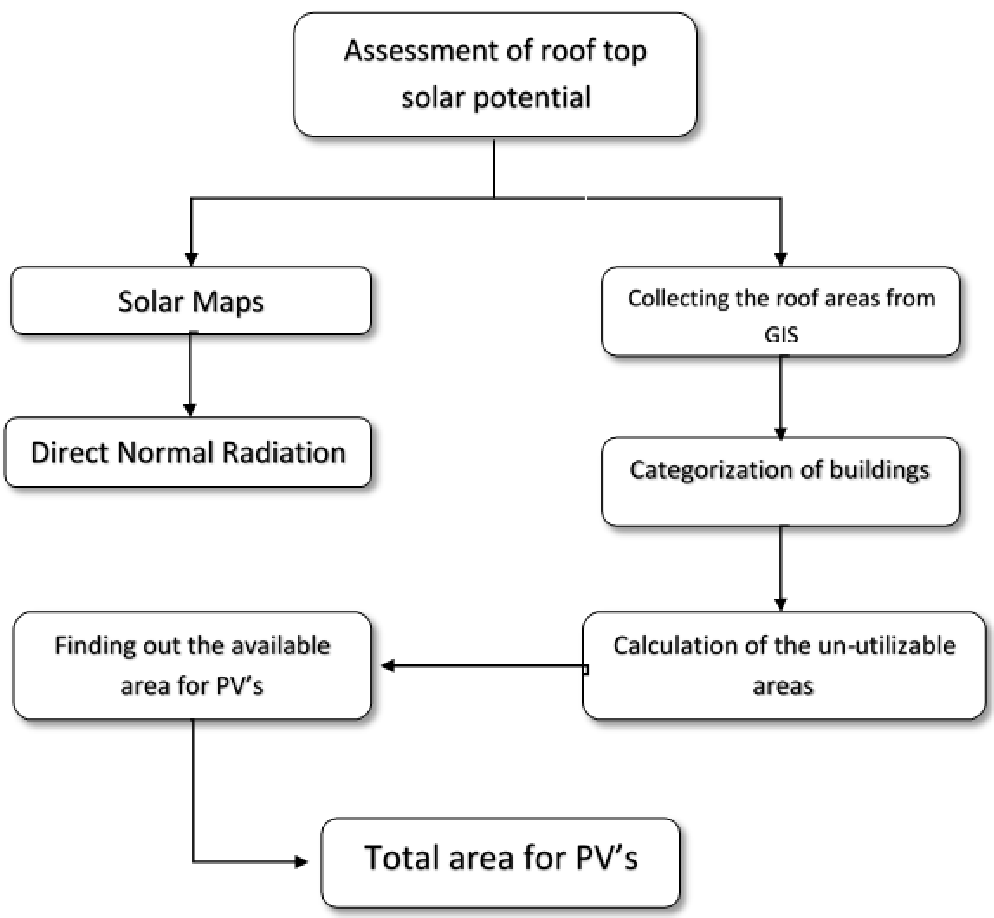


Figure 21: Assessment of roof top solar potential flow chart

3.2.3 Power potential of solar PV

Optimization and energy potential for roof top PV panels are shown in Figure 22. This will include investigation of two choices of electricity generation by applying solar PV panels in the following two cases:

- Inclined or tilted photovoltaic panels with the optimal inclination angle related to the study area.

- Horizontal or untitled panels applied directly on the rooftop.

The simulations for power generation were done by PVsyst software.

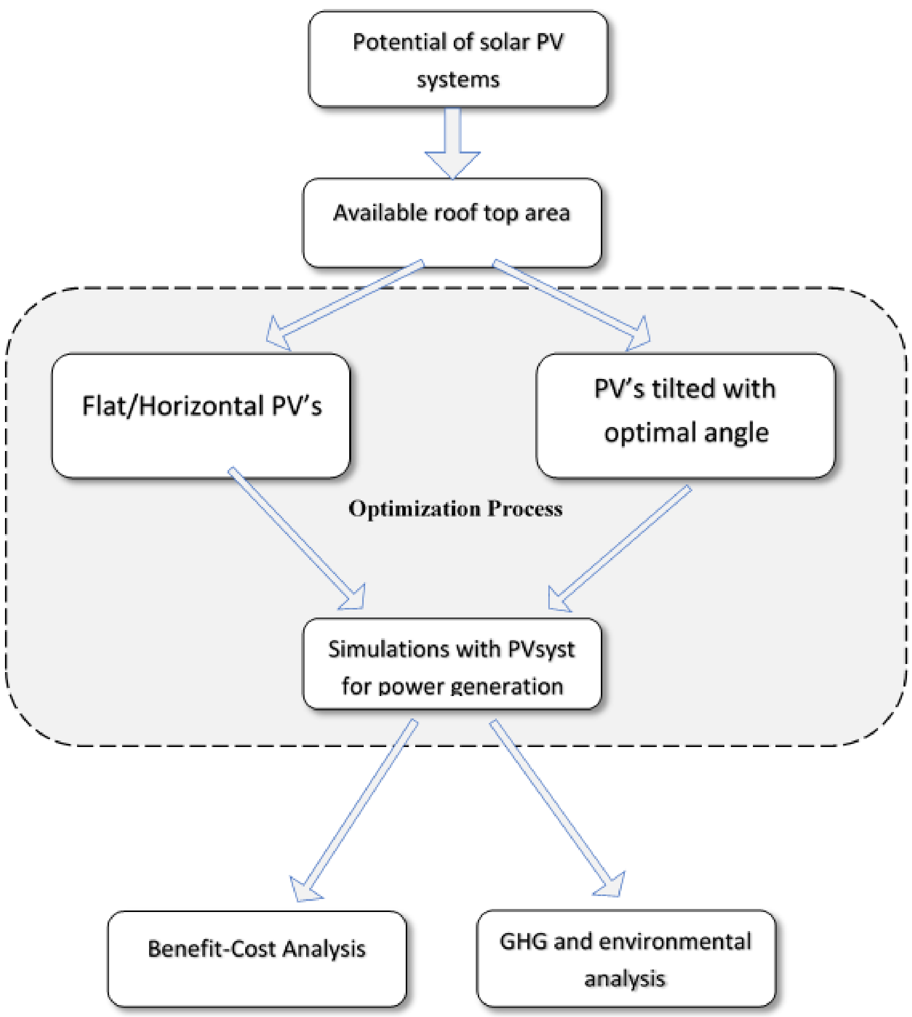


Figure 22: Potential of solar PV panels flow chart

3.2.4 Benefit - cost analysis

The economic feasibility is investigated by the benefit-cost analysis. Figure 23 shows the detailed analysis process. The following steps summarize the methodology

- Calculation of the initial investment of the PV systems.
- Calculation of the operational and maintenance costs.
- Calculation of inverters replacement costs.
- Finding out the net present value NPV of the previous three mentioned costs.
- Convert the NPV to annual costs over the project’s life cycle.
- Estimating the annual benefits from the generated energy.
- Calculation of benefit to cost ratio.

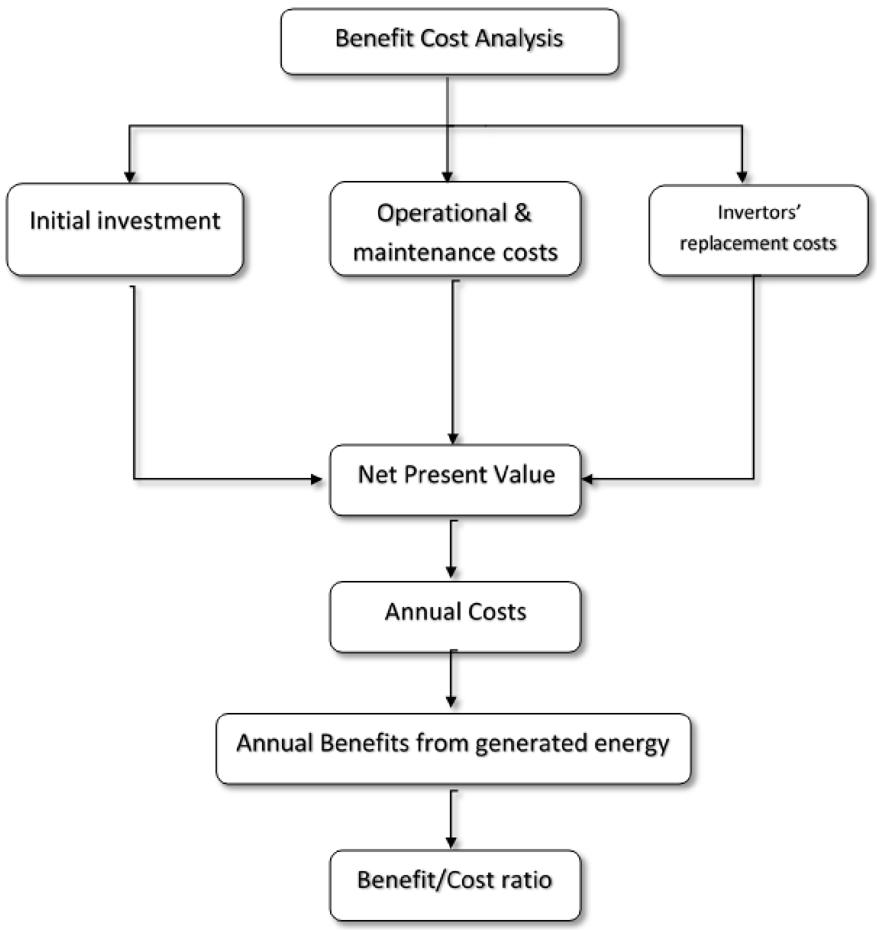


Figure 23: Benefit Cost Analysis flow chart

3.2.5 Environmental analysis

For the environmental analysis, the greenhouse gases (GHG) were calculated and estimated. The energy mix for Saudi Arabia was identified, and the factors for energy conversion to GHG were collected from the literature. These gases include:

1- Carbon dioxide. The conversion factor is 0.816 (Metric tons/MWh).
2- Methane. The conversion factor is 0.02678 (kg/ MWh).
3- Nitrous oxide. The conversion factor is 0.00487 (kg /MWh).

CHAPTER 4

DATA ANALYSIS AND RESULTS

4.1 Introduction

The main characteristics that should be available within the renewable energy supply source are environmentally sustainable and safe. Implies less risk of accidents as much as possible. Such source of energy should also be in large-scale supply, to ensure its long-term availability (Arnulf, 2007). The increased adoption and evolution of the renewable energy supplies, offer viable solutions for environmental crises caused by conventional energy sources (Michael, 2006). Solar energy plays an important role in this regard, as it offers a clean, safe, and huge source of renewable energy.

In this chapter, all the data pertaining the solar potential of Dhahran area on which KFUPM is located is addressed and presented. It also presents two cases of implementing the photovoltaic systems on the rooftop of KFUPM buildings. Firstly, the photovoltaic PV panels were implemented on the same area tilted with the optimal inclination angel associated with Dhahran area. Secondly, the panels were implemented horizontally with tilt angel equal to zero.

The areas and its utilization with solar panels will be investigated in details. Finally, the results obtained from the optimization process of the pre-mentioned two cases together with the economic and environmental analysis are also presented and discussed.

4.2 Evaluation of solar energy in Dhahran, KSA

Dhahran is located in the Eastern Province of Saudi Arabia. It is situated on 26°18'29" North, and 50°9'1" East, with an elevation of 62 m above mean sea level. Figure 24 shows an aerial view of Dhahran area. The optimal inclination angle for solar panels is 24 degrees. Table 6 shows the annual irradiation incident on Dhahran (European Commission, Joint Research Centre).

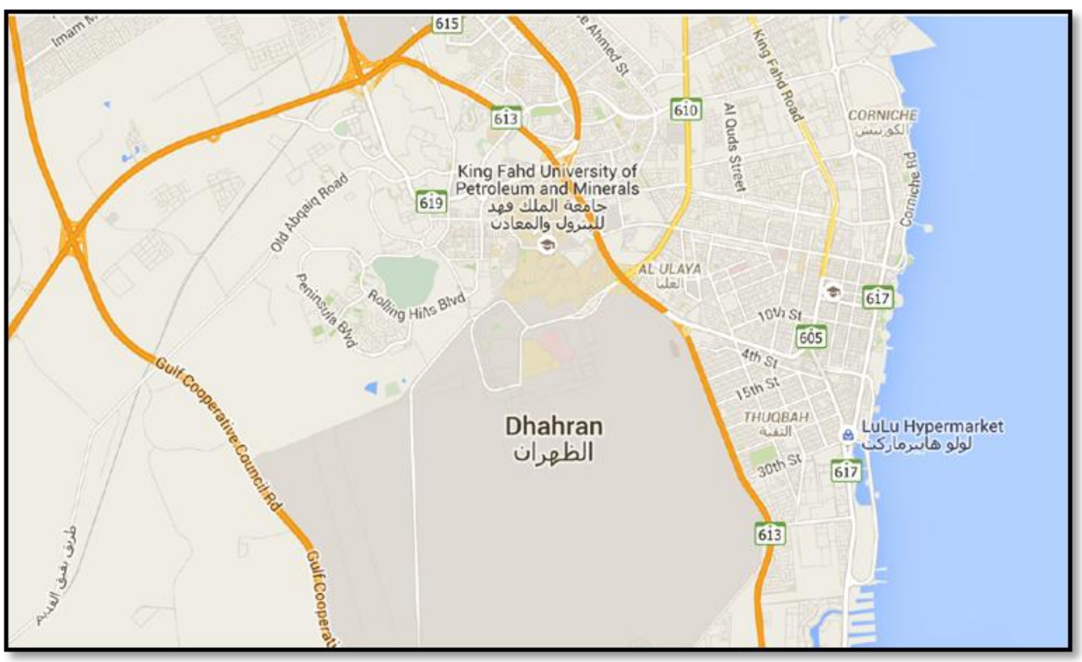


Figure 24: Aerial photo of Dhahran area (Google maps, 2015)

Table 6: Annual irradiation incident on Dhahran (Joint Research Centre)

Month	Hh (Wh/m²/day)	Hopt. (Wh/m²/day)	DNI (Wh/m²/day)	Iopt. (deg.)
Jan	3880	5090	4360	52
Feb	4800	5830	4810	43
Mar	6070	6730	5580	30
Apr	6600	6670	5540	14
May	7790	7340	6750	1
Jun	8320	7520	7720	0
Jul	7860	7270	6800	1
Aug	7440	7310	6620	9
Sep	6910	7450	6910	25
Oct	5750	6870	6340	40
Nov	4170	5320	4430	49
Dec	3730	5040	4450	54
Year	**6120**	**6540**	**5870**	**24**

Where:

Hh: Irradiation on horizontal plane

$H_{opt.}$: Irradiation on optimally inclined plane

DNI: Direct normal irradiation

$I_{opt.}$: Optimal inclination

It can be noticed that Dhahran area has the maximum solar irradiation in the summer months May, June, and July. The maximum incident irradiation on the optimal inclination angle of 24-degree is 7520 (Wh/m^2/day).

The optimal inclination angle for each month in Dhahran is shown in Figure 25. On the other hand, Figure 26 represents the monthly solar irradiation on Dhahran.

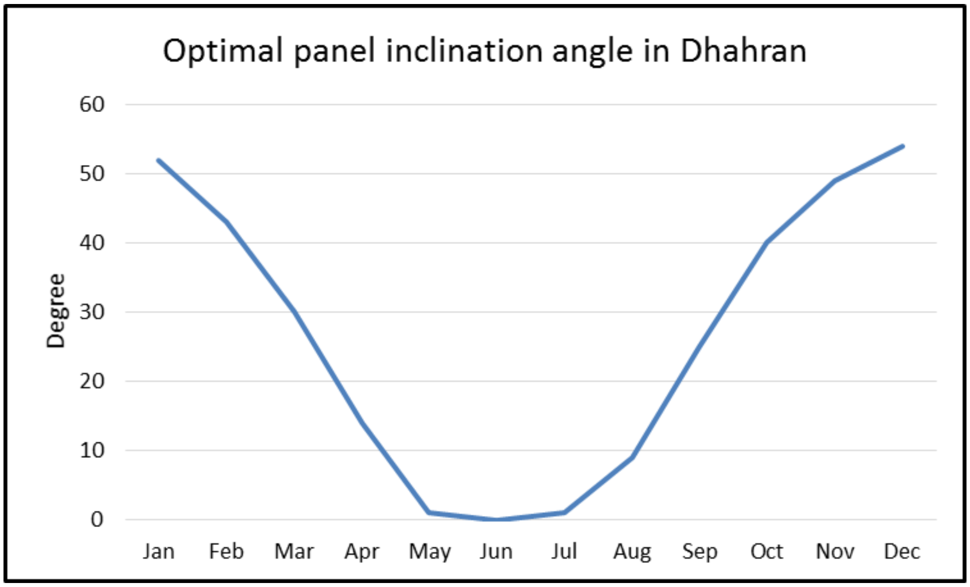


Figure 25: Optimal inclination angle in Dhahran (Joint Research Centre, 2015)

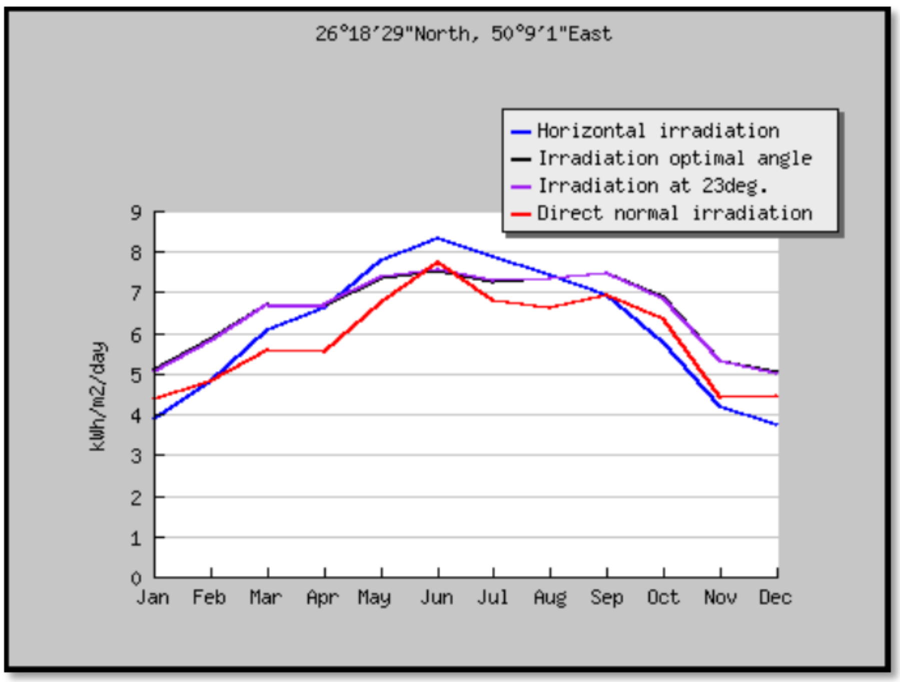


Figure 26: Solar irradiation on Dhahran (Joint Research Centre)

Figure 27 and Figure 28 reveal the solar paths at Dhahran. It can be noticed that the sun will almost be perpendicular at noontime if the azimuth is zero.

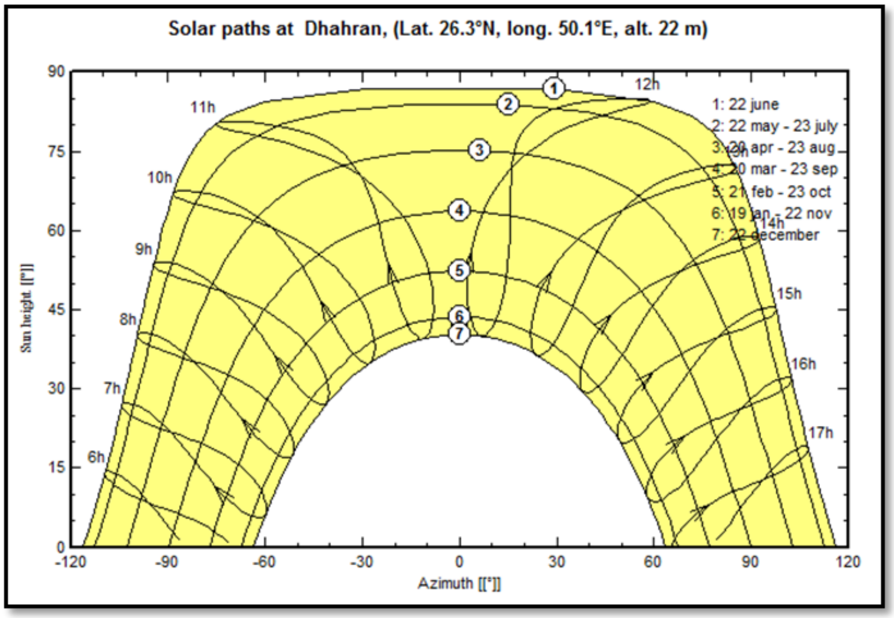


Figure 27: Solar path at Dhahran (PVsyst software)

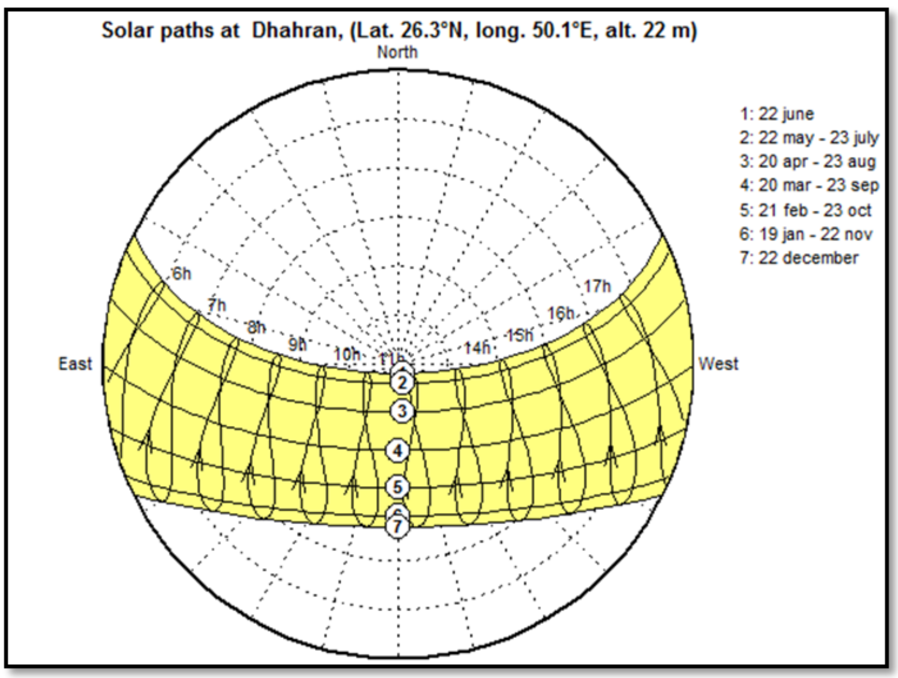


Figure 28: Solar path at Dhahran in polar form (PVsyst software)

4.3 Determination of roof top utilizable areas

All the buildings data for KFUPM were extracted and categorized with the help of ArcGIS software. Building types were categorized into seven categories. The summation of the total roof top areas is shown in Table 7 and the areas distribution is shown in Figure 29.

Table 7: Total roof top areas for KFUPM

Building type	Total Roof Area (m^2)
Parking areas.	352244
Faculty housing	157153
Support facilities.	130711
Academic buildings	97232
Student housing.	91299
Labor and staff housing.	17338
Mosques	11432
Total Area	**857408**

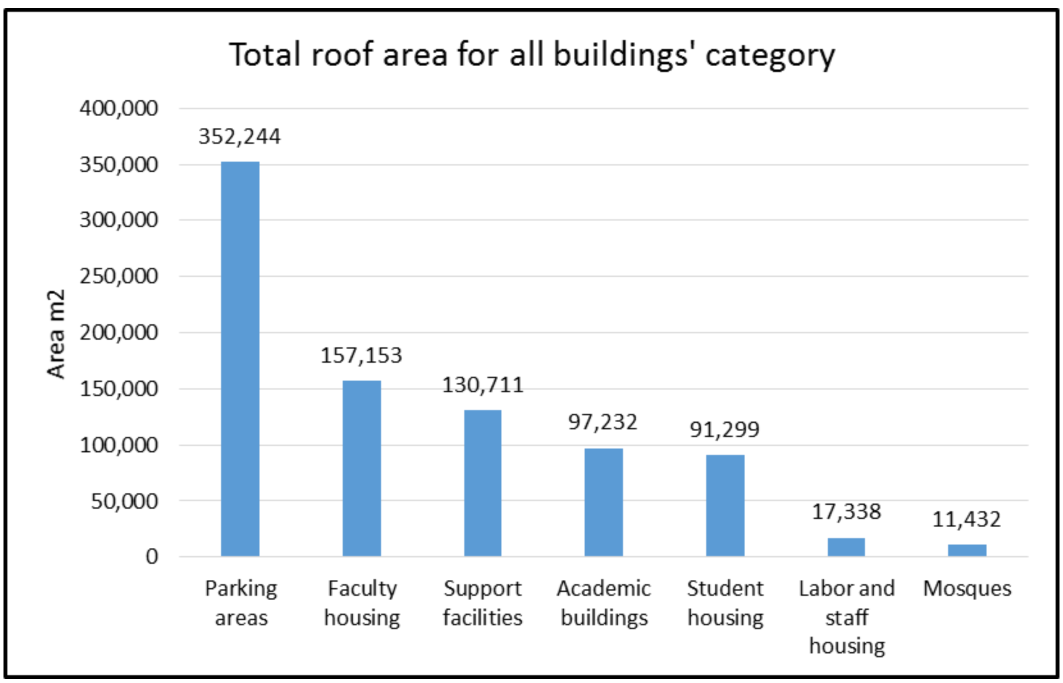


Figure 29: KFUPM building's rooftop areas

A sample building was chosen for each category from the campus, and was analyzed to find out the percentage of its rooftop area used for PV panels from the building's total roof area. This was done first by digitizing the building using AutoCAD software with the help of aerial photos taken from Google maps. Then, the total roof top area was estimated. The un-utilizable areas that indicates the areas obstructed by other building systems such as HVAC systems, sky light openings, and vents for plumping or mechanical installations were calculated. These areas represent the areas on which photovoltaic systems could not be implemented.

A 250 Wp mono crystalline, 60 cells photovoltaic module was a assumed to be used in this study. Each module is (1.65*1.00) m in dimension. See appendix A for full technical specifications of the modules. Then, the modules were drawn in AutoCAD for each sample building twice assuming the following cases:

- PV panels are tilted with 24˚ optimal angle. See Figure 30.
- PV panels are horizontal or flat with zero tilt angle. See Figure 31.

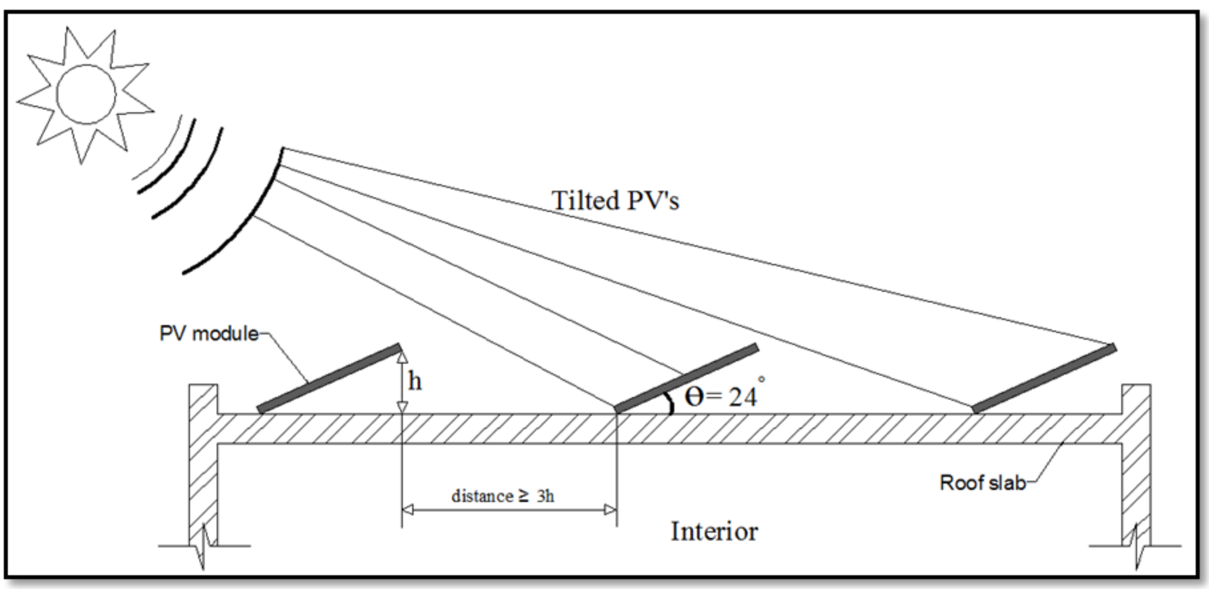


Figure 30: Tilted PV panels

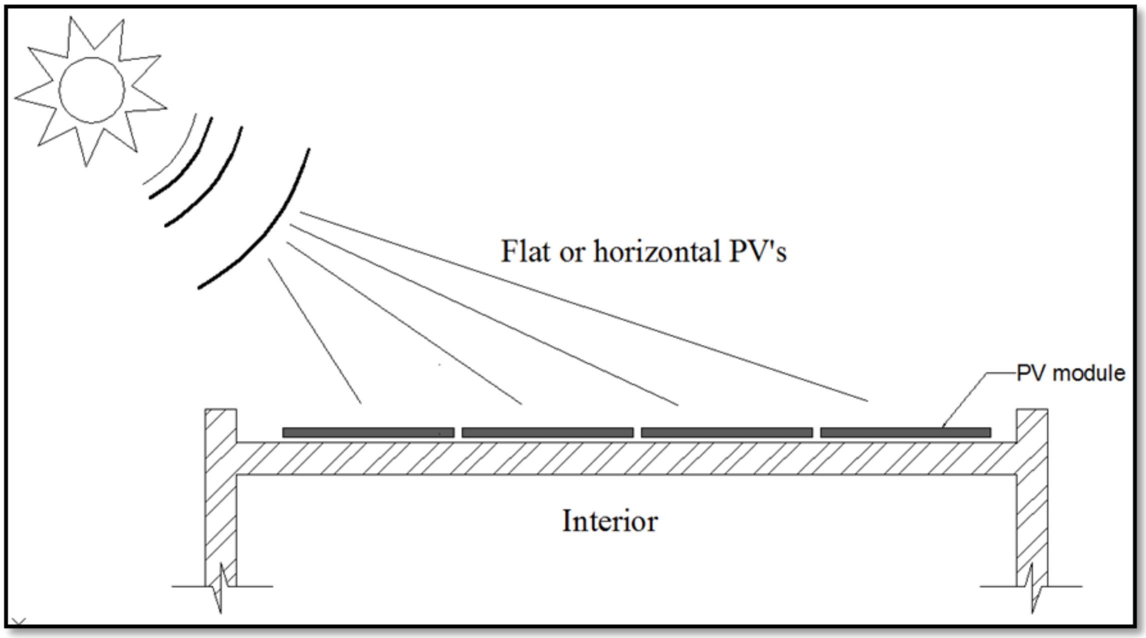


Figure 31: Flat or horizontal PV panels

Finally, the total number of PV panels for the two cases was counted and recorded. The total area of PV panels was also calculated. Then, the percentage of the roof top used for PVs from the building's total roof area was calculated. See appendix B for more details.

4.3.1 PV panels are tilted 24°

Table 8 shows all the previous details and calculations. It can be noticed that the rooftop of parking buildings cannot be utilized because the roofs were completely designed to be parking area too.

Table 8: Information and calculations for building's roof top areas (tilted PV panels with 24°)

	Academic Buildings	Faculty housing	Support facilities	Student Housing	Labor and staff housing	Mosques	Parking areas
Building rooftop area m^2 (Sample Building)	7411	235	4800	1300	120	537	9320
Un-utilizable area m^2	525	78	505	206	0	58	9320
number of PVs	1781	36	1135	267	30	113	0
Area of PVs m^2	2938.65	59.4	1872.75	440.55	49.5	186.45	0
Utilizable area m^2	6886	157	4295	1094	120	479	0
(%) of rooftop used for PVs from the building's utilizable area	43	38	44	40	41	39	0
(%) of rooftop used for PVs from the building's total roof area	40	25	39	34	41	35	0

Sample calculation for Academic building (tilted PV panels with 24°):

- Building rooftop area = 7411 m^2.
- Un-utilizable area = 525 m^2.
- Utilizable area = 7411- 525= 6886 m^2.
- Number of PVs = 1781.
- Area of PV panels = (1*1.65) * 1781= 2938.65 m^2.
- Percentage of rooftop used for PVs from the building's utilizable area = $\frac{2938.65}{6886} \times 100\% = 43\%$.
- Percentage of rooftop used for PVs from the building's total roof area = $\frac{2938.65}{7411} \times 100\% = 40\%$.

Figure 32, Figure 33, Figure 34, and Figure 35 show in details the results obtained in Table 8.

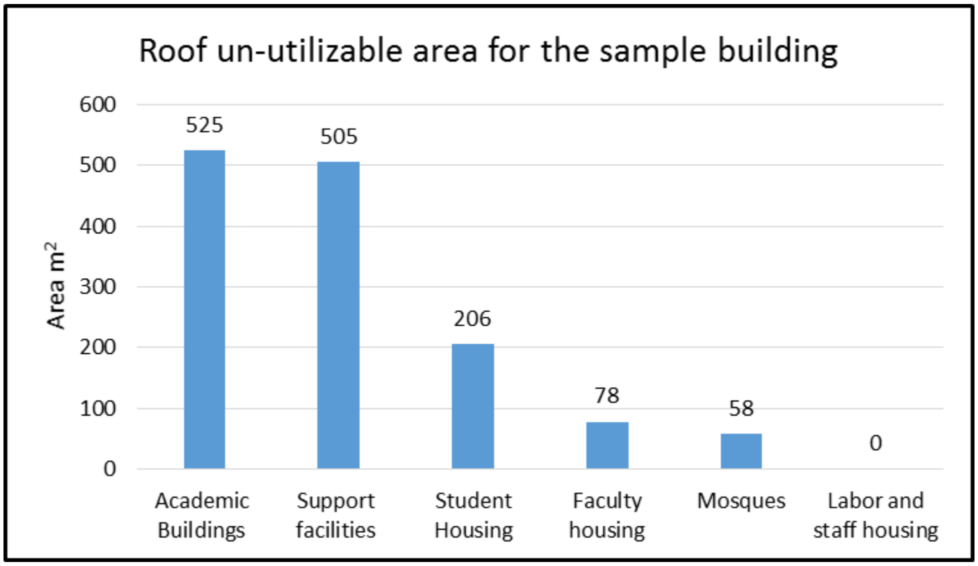


Figure 32: Roof un-utilizable area (tilted PV 24˚)

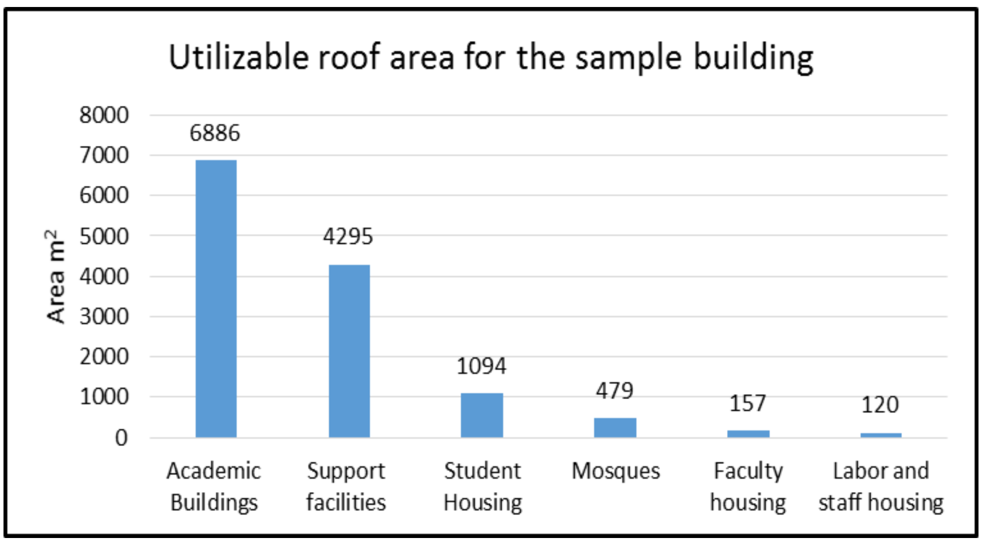


Figure 33: Utilizable roof area for the sample building (tilted PV 24˚)

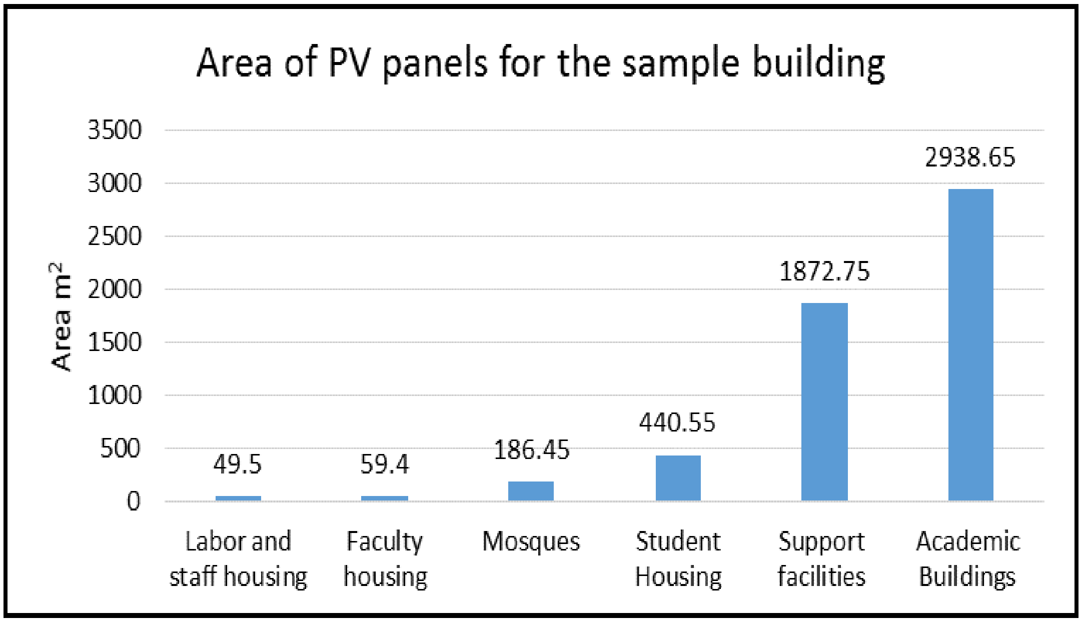


Figure 34: Area of PV panels for the sample building (tilted PV 24˚)

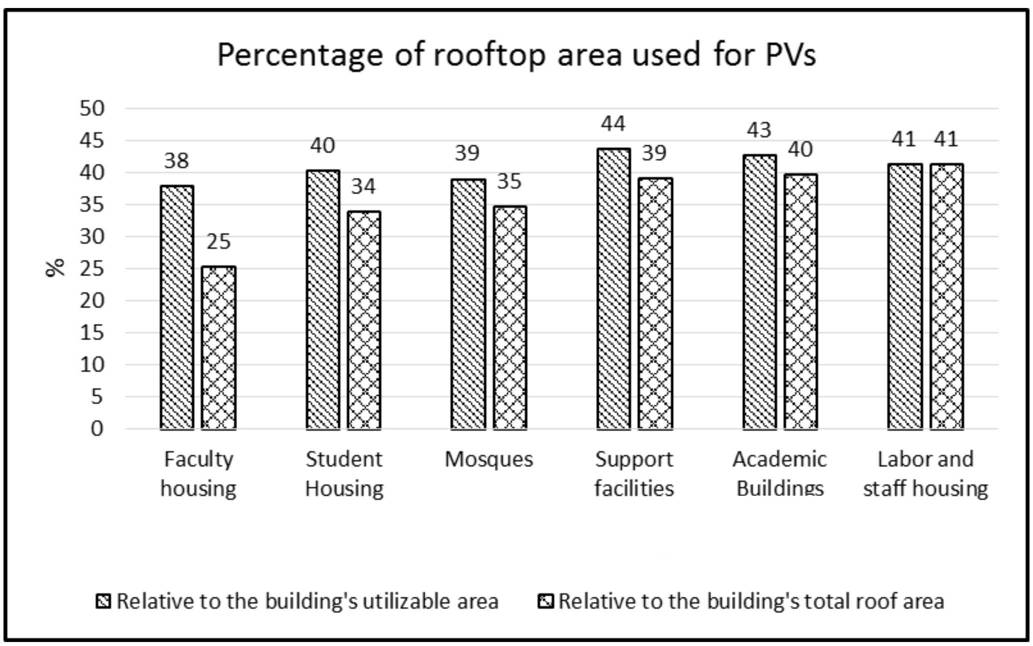


Figure 35: Percentage of rooftop area used for PVs in the sample building (tilted PV 24˚)

The final results of the analysis were reflected to all the buildings in KFUPM and shown in Table 9.

Table 9: Total roof top areas for KFUPM assuming tilted PV with 24 degree.

Building type	Total Roof Area (m^2)	Percentage of rooftop used for PVs from the building's total roof area (%)	Total Area of PVs
Parking areas	352244	0	**0**
Faculty housing	157153	25	**39,288**
Support facilities	130711	39	**50,977**
Academic buildings	97232	40	**38,893**
Student housing	91299	34	**31,042**
Labor and staff housing	17338	41	**7,109**
Mosques	11432	35	**4,001**
Total			**171,310**

It is clear that the support facilities category possesses the larges area of proposed PV panels, then, comes faculty housing and the academic buildings. See Figure 36 and Figure 37.

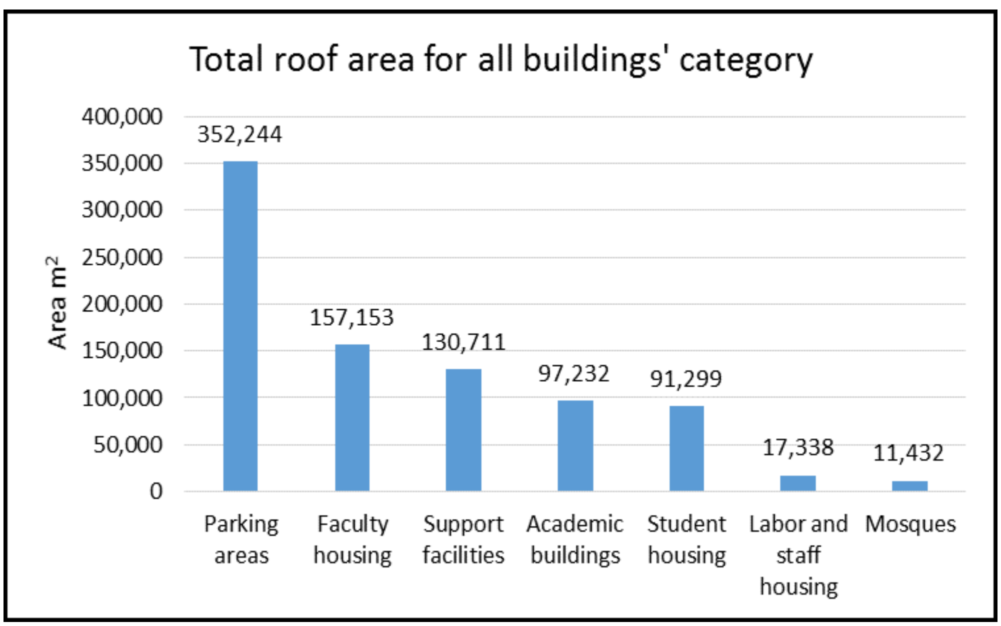


Figure 36: Total roof area for all buildings' category in KFUPM (tilted PV panels)

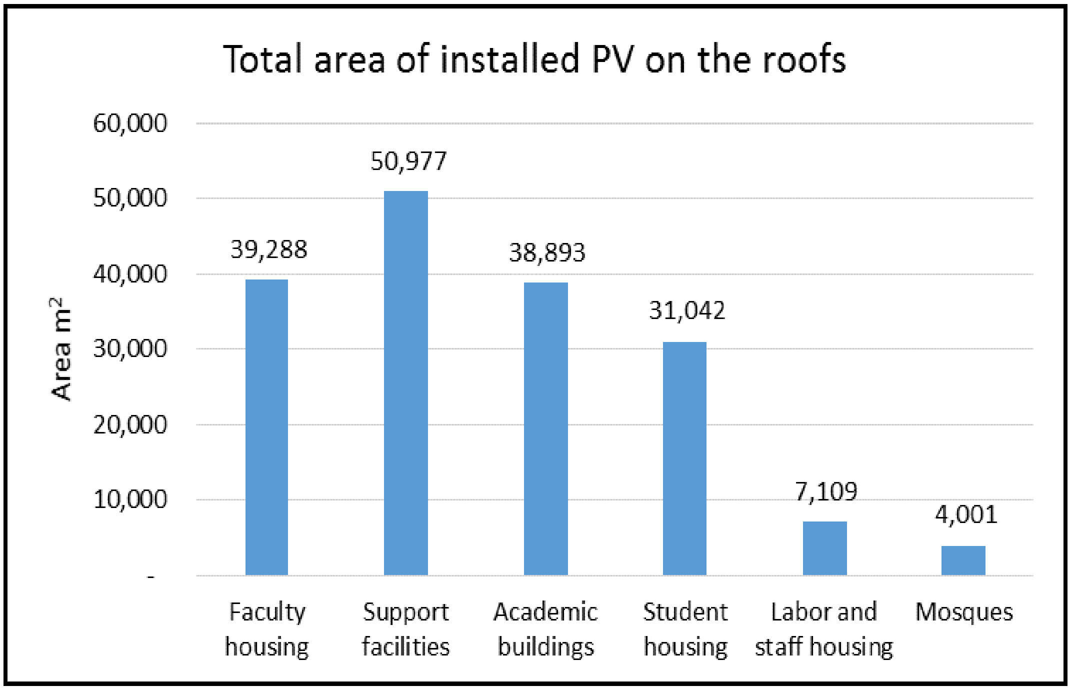


Figure 37: Total area of installed PV on the roofs (tilted PV panels)

It can be noticed from the previous graph that the support facilities category can accommodate the largest portion of the proposed PV systems on its roof tops of about 50,977 m^2 of PV panels, then, comes the faculty housing of 39,288 m^2, and the academic building of 38,893 m^2, then the student housing of 31,042 m^2, then the labor and staff housing of 7,109 m^2, finally, comes the mosques, which accommodates the least area of PV panels of 4,001 m^2.

4.3.2 Flat or horizontal PV panels

Table 10 shows all the necessary details and calculations. It can be noticed that the rooftop of parking areas cannot be utilized because the roof was completely designed to be a parking area too.

Table 10: Information and calculations for building's roof top areas (Flat PV panels)

	Academic Buildings	Faculty housing	Support facilities	Student Housing	Labor and staff housing	Mosques	Parking areas
Building rooftop area m^2 (Sample Building)	7411	235	4800	1300	120	537	9320
Un-utilizable area m^2	525	78	505	206	0	58	9320
number of PVs	2307	53	1566	373	36	149	0
Area of PVs m^2	3806.55	87.45	2583.9	615.45	59.4	245.85	0
Utilizable area m^2	6886	157	4295	1094	120	479	0
(%) of rooftop used for PVs from the building's utilizable area	55	56	60	56	50	51	0
(%) of rooftop used for PVs from the building's total roof area	51	37	54	47	50	46	0

Sample calculation for Academic building (Flat PV panels):

- Building rooftop area = 7411 m^2.
- Un-utilizable area = 525 m^2.
- Utilizable area = 7411- 525= 6886 m^2.
- Number of PVs = 2307.
- Area of PV panels = (1*1.65) * 2307= 3806.55 m^2.
- Percentage of rooftop used for PVs from the building's utilizable area = $\frac{3806.55}{6886} \times 100\% = 55\%$.
- Percentage of rooftop used for PVs from the building's total roof area =$\frac{3806.55}{7411} \times 100\% = 51\%$.

Figure 38, Figure 39, Figure 40, and Figure 41 show in details the results obtained in Table 10.

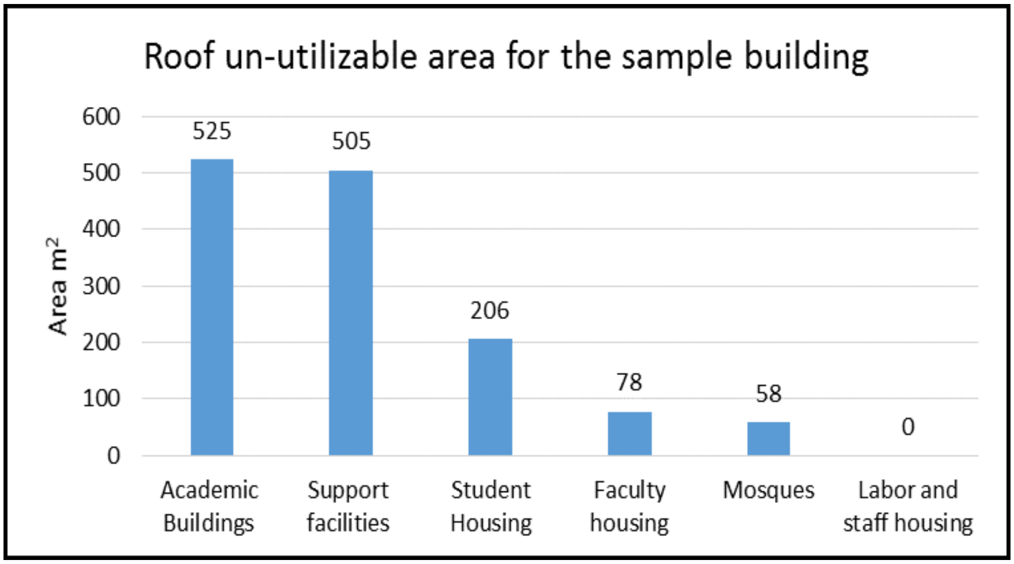


Figure 38: Roof un-utilizable area (Flat PV)

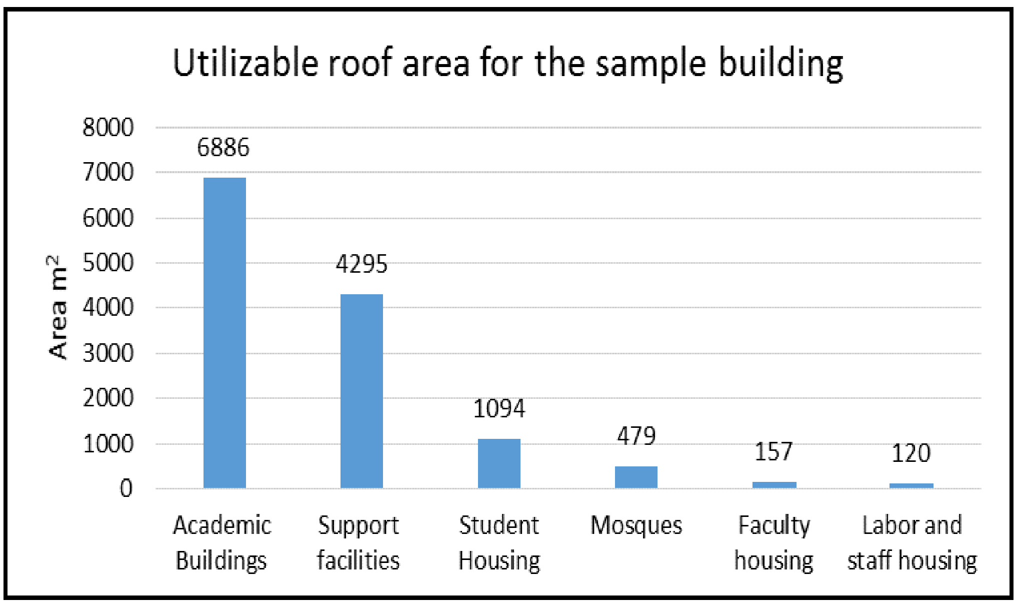


Figure 39: Utilizable roof area for the sample building (Flat PV)

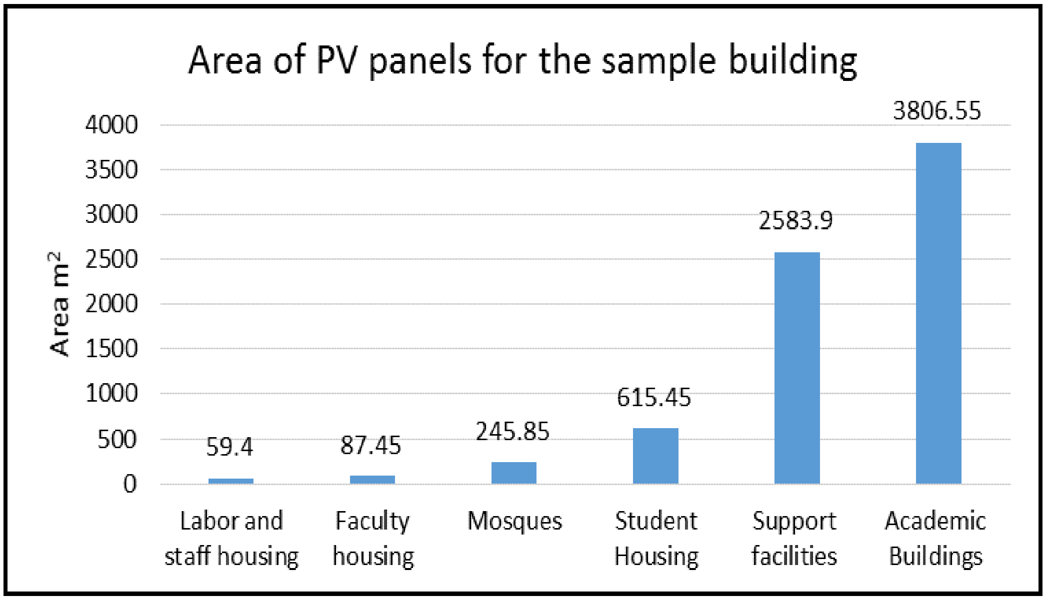


Figure 40: Area of PV panels for the sample building (Flat PV)

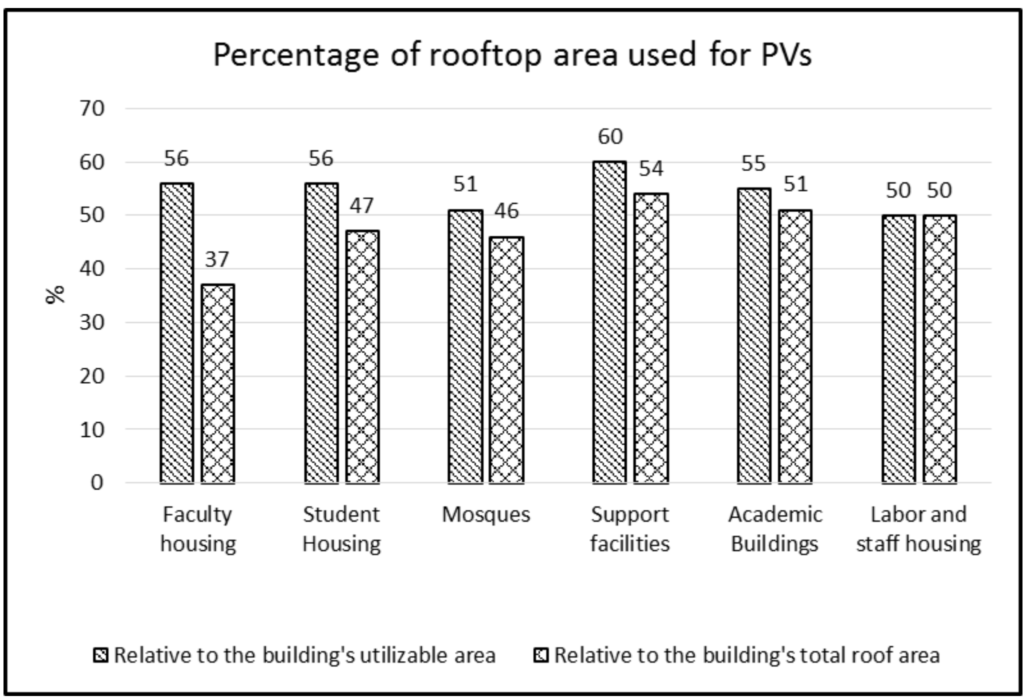


Figure 41: Percentage of rooftop area used for PVs in the sample building (Flat PV)

The final results of the analysis were reflected to all the buildings in KFUPM and shown in Table 11.

Table 11: Total roof top areas for KFUPM assuming flat PV

Building type	**Total Roof Area (m^2)**	**Percentage of rooftop used for PVs from the building's total roof area (%)**	**Total Area of PVs**
Parking areas	352244	0	**0**
Faculty housing	157153	37	**58,147**
Support facilities	130711	54	**70,584**
Academic buildings	97232	51	**49,588**
Student housing	91299	47	**42,911**
Labor and staff housing	17338	50	**8,669**
Mosques	11432	46	**5,259**
Total			**235,157**

It is clear that the support facilities category possesses the largest area of proposed PV panels, then, comes faculty housing and the academic buildings. See Figure 42 and Figure 43.

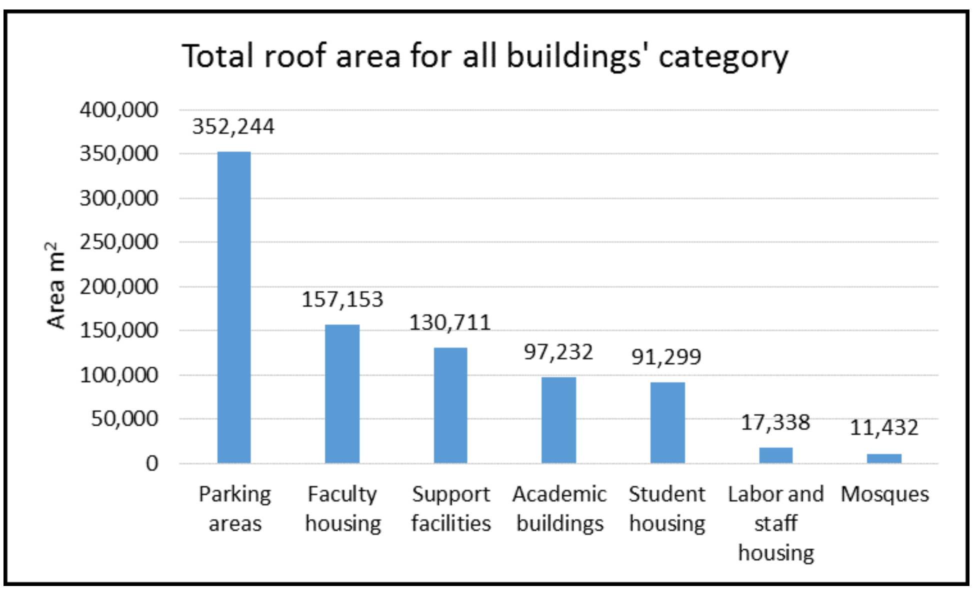


Figure 42: Total roof area for all buildings' category (Flat PV panels)

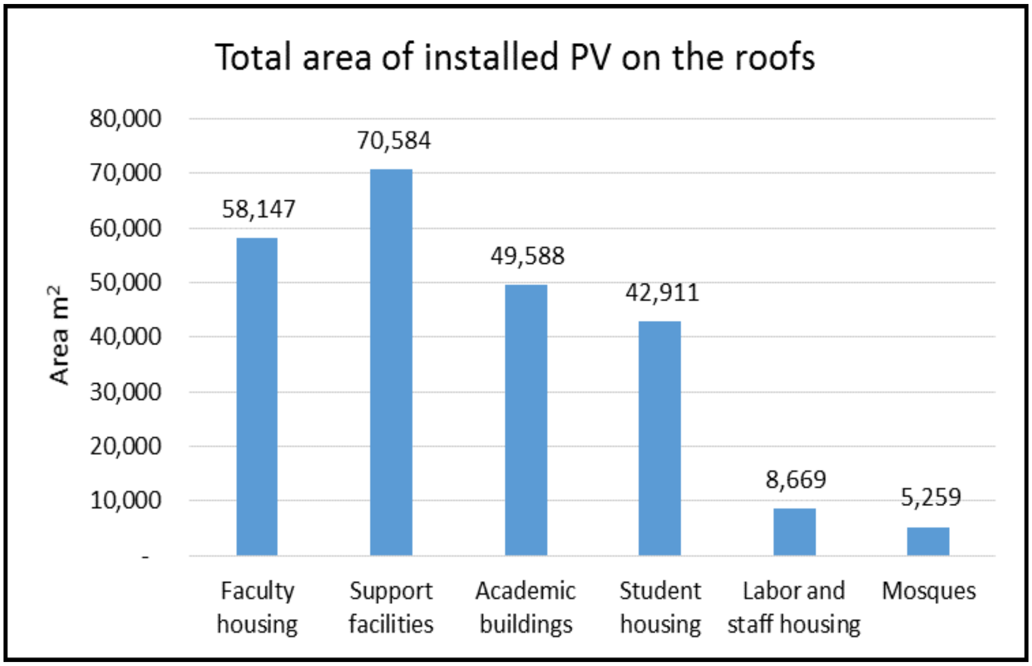


Figure 43: Total area of installed PV on the roofs (Flat PV panels)

It can be noticed from the previous graph that the support facilities category can accommodate the largest portion of the proposed PV systems on its roof tops of about 70,584 m^2 of PV panels, then, comes the faculty housing of 58,147 m^2, and the academic building of 49,588 m^2, then the student housing of 42,911 m^2, then the labor and staff housing of 8,669 m^2, finally, comes the mosques, which accommodates the least area of PV panels of 5,259 m^2.

4.4 Design and optimization of roof top solar PV

Design phases and simulations were carried out using PVsyst software. In the design phase, the number of mono 250 Wp 60 cells and 12 kWac inverter with 2 MPPT inverters were calculated. The optimization process was done between the two possible cases of implementing the photovoltaic panels (i.e. tilted and flat PV panels). The nominal capacity generated from the PV arrays was recorded. Then, the inverters pack capacity to the grid was also estimated. Finally, the system production or the annual produced energy was found out.

Note: All of the simulations were carried out for a whole year.

4.4.1 PV panels are tilted 24°.

The output results of the design and optimized simulation of the systems were found for each area category:

1) Academic buildings. All the results including: system design and outputs, the normalized production, the performance ratio, loss diagram over the whole year are represented in Figure 44, Figure 45, Figure 46, and Table 12.

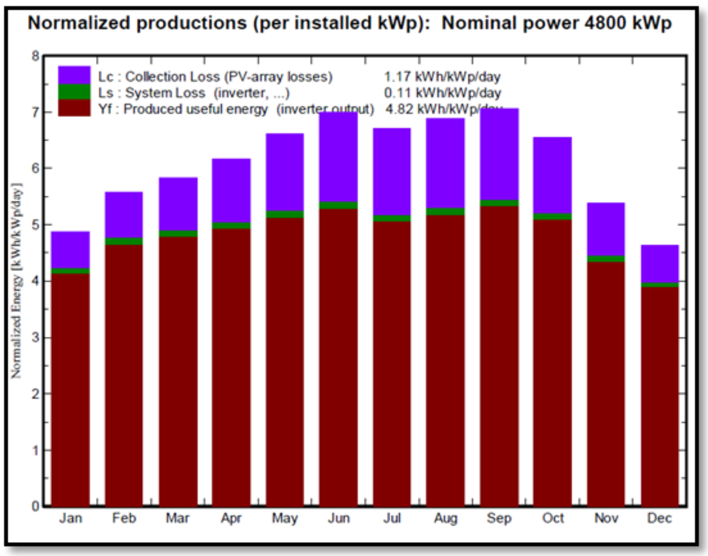


Figure 44: Normalized productions for Academic buildings (tilted PV panels) (Source: PVsyst)

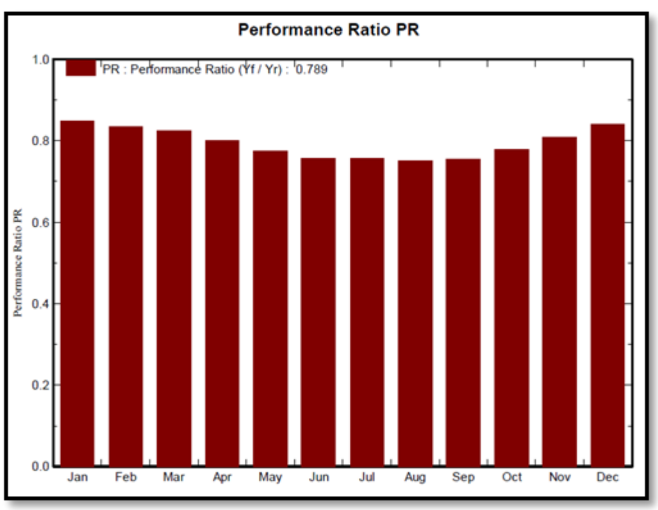


Figure 45: Performance ratio for Academic buildings (tilted PV panels) (Source: PVsyst)

Table 12: Output results for Academic buildings (tilted PV)

System parameter	Output
Number of PV modules	19200
Pnom total	4800 kWp
Number of inverters	384
Inverters Pnom total	4608 kW AC
Produced Energy	8450 MWh/year
Specific production	1760 kWh/kWp/year
Performance ratio	78.9 %

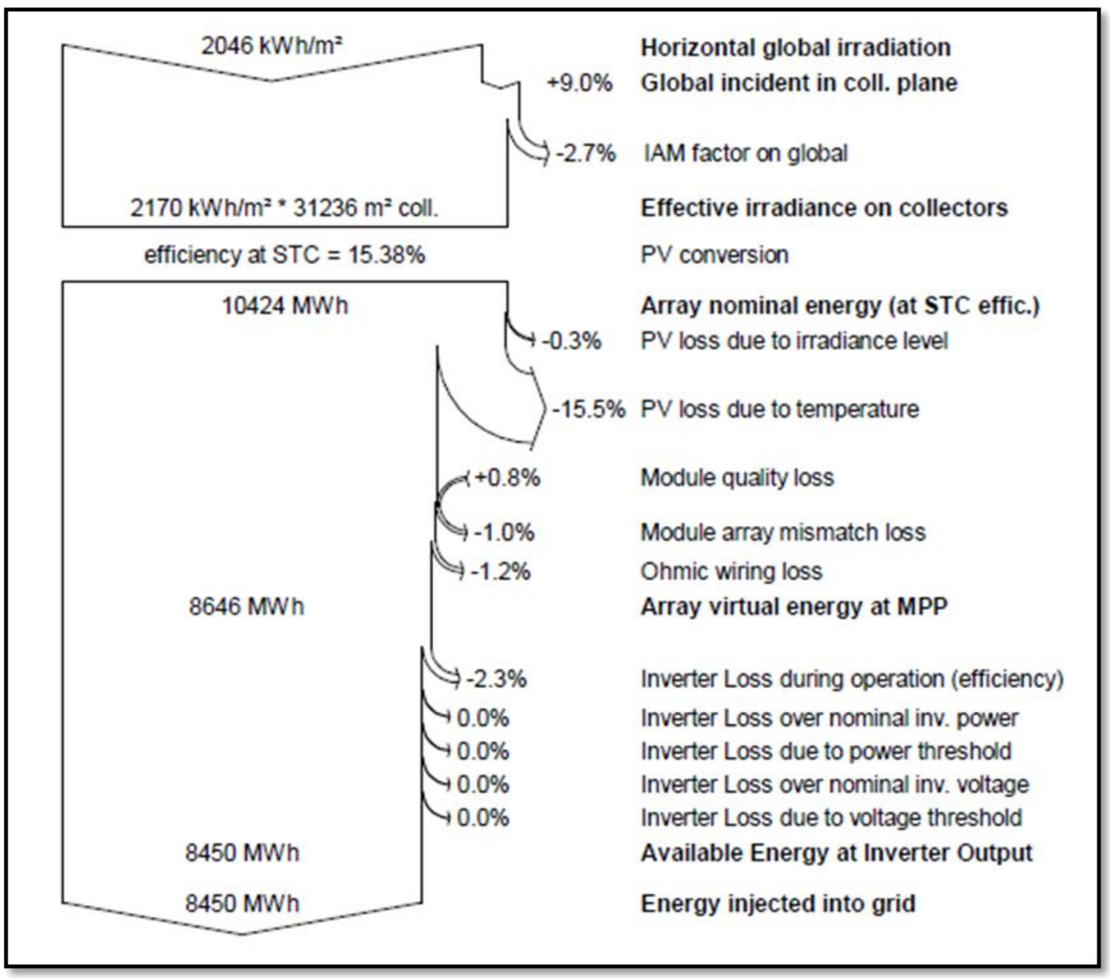


Figure 46: Loss diagram for Academic Buildings (Tilted PV panels) (Source: PVsyst)

2) Faculty housing. The key results are shown in Table 13. For more results, see appendix C.

Table 13: Output results for Faculty housing (tilted PV)

System parameter	Output
Number of PV modules	20160
Pnom total	5040 kWp
Number of inverters	388
Inverters Pnom total	4656 kW AC
Produced Energy	8871 MWh/year
Specific production	1760 kWh/kWp/year
Performance ratio	78.9 %

3) Labor and staff housing. The key results are shown in Table 14. For more results, see appendix C.

Table 14: Output results for Labor and staff housing (tilted PV)

System parameter	Output
Number of PV modules	3570
Pnom total	893 kWp
Number of inverters	71
Inverters Pnom total	852 kW AC
Produced Energy	1571 MWh/year
Specific production	1760 kWh/kWp/year
Performance ratio	78.9 %

4) Mosques. The key results are shown in Table 15. For more results see appendix C.

Table 15: Output results for Mosques (tilted PV)

System parameter	Output
Number of PV modules	2040
Pnom total	510 kWp
Number of inverters	40
Inverters Pnom total	480 kW AC
Produced Energy	897.9 MWh/year
Specific production	1761 kWh/kWp/year
Performance ratio	78.9 %

5) Student housing. The key results are shown in Table 16. For more results, see appendix C.

Table 16: Output results for Student housing (tilted PV)

System parameter	Output
Number of PV modules	15300
Pnom total	3825 kWp
Number of inverters	306
Inverters Pnom total	3672 kW AC
Produced Energy	6733 MWh/year
Specific production	1760 kWh/kWp/year
Performance ratio	78.9 %

6) Support facilities. The key results are shown in Table 17. For more results, see appendix C.

Table 17: Output results for Support facilities (tilted PV)

System parameter	Output
Number of PV modules	25500
Pnom total	6375 kWp
Number of inverters	503
Inverters Pnom total	6036 kW AC
Produced Energy	11223 MWh/year
Specific production	1761 kWh/kWp/year
Performance ratio	78.9 %

4.4.2 Flat or horizontal PV panels

The output results of the design and optimized simulation of the systems were found for each area category:

1) Academic buildings. All the results including: system design and outputs, the normalized production, the performance ratio, loss diagram over the whole year are represented in Figure 47, Figure 48, Figure 49, and Table 18.

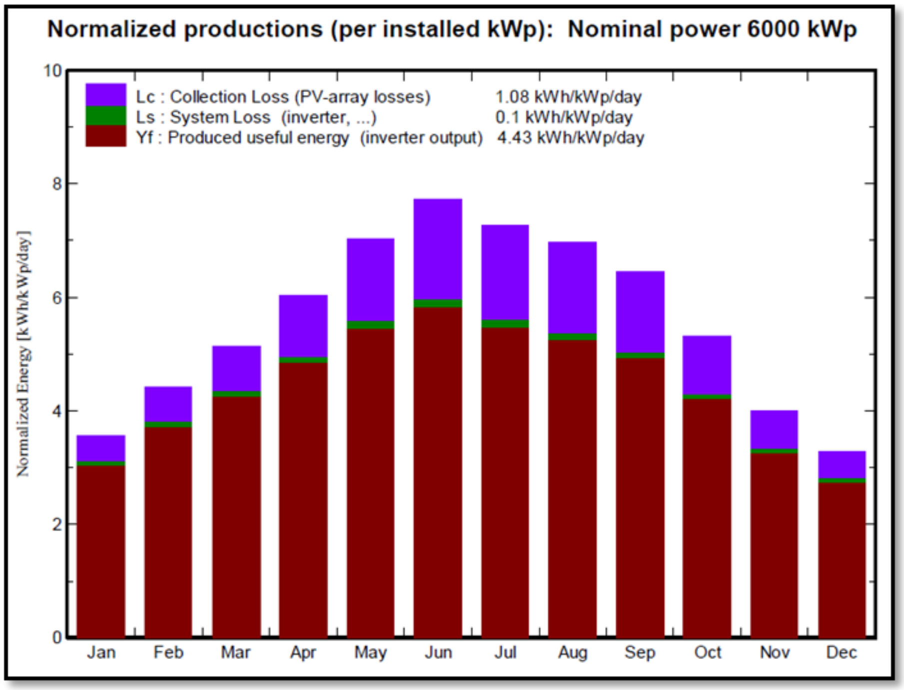


Figure 47: Normalized productions for Academic buildings (Flat PV panels) (Source: PVsyst)

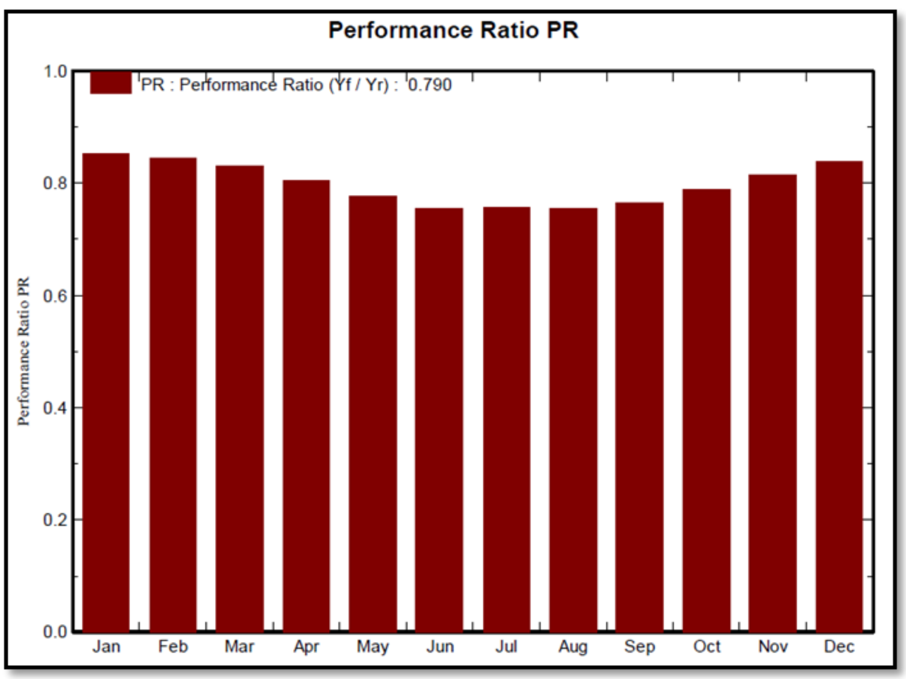


Figure 48: Performance ratio for Academic buildings (Flat PV panels) (Source: PVsyst)

Table 18: Output results for Academic buildings (Flat PV)

System parameter	Output
Number of PV modules	24000
Pnom total	6000 kWp
Number of inverters	489
Inverters Pnom total	5868 kW AC
Produced Energy	9693 MWh/year
Specific production	1615 kWh/kWp/year
Performance ratio	79.0 %

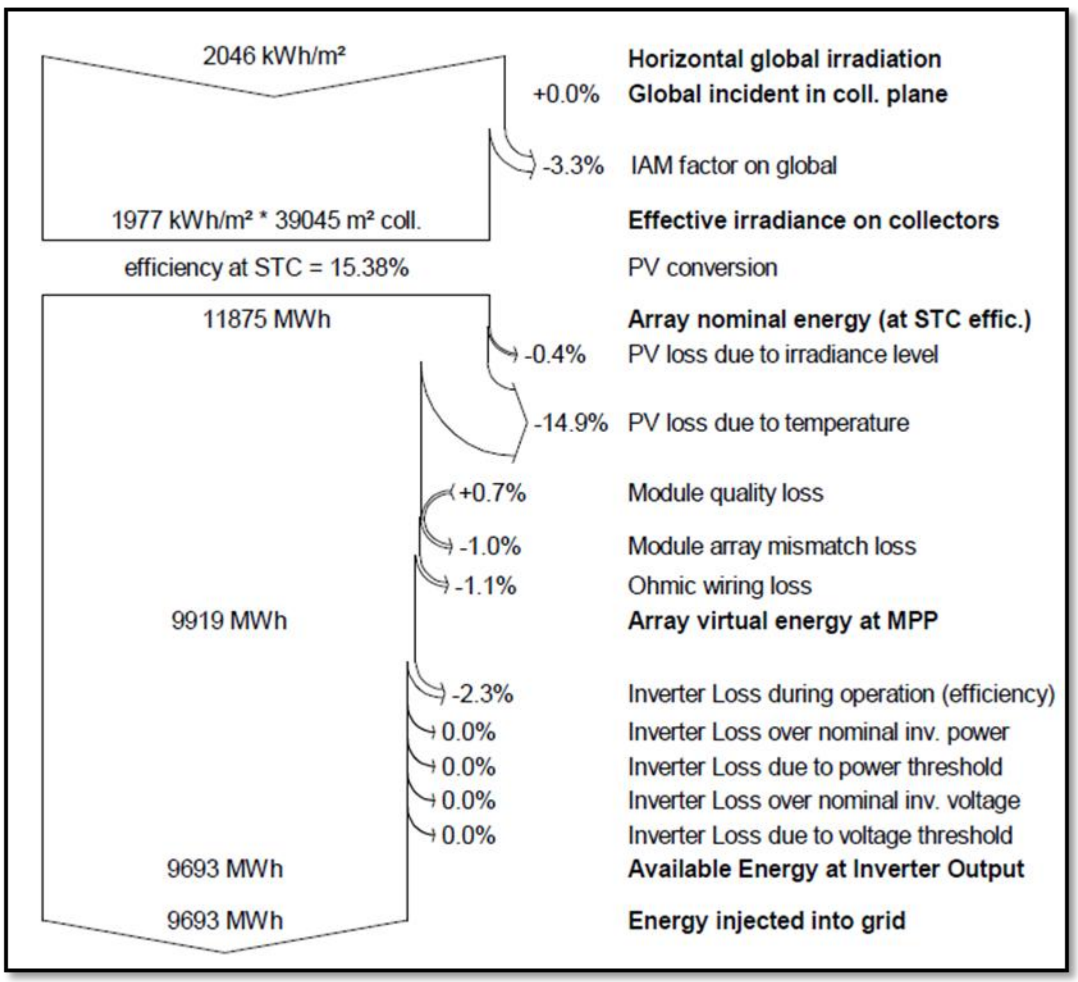


Figure 49: Loss diagram for Academic Buildings (Flat PV panels) (Source: PVsyst)

2) Faculty housing. The key results are shown in Table 19. For more results, see appendix C.

Table 19: Output results for Faculty housing (Flat PV)

System parameter	Output
Number of PV modules	28900
Pnom total	7225 kWp
Number of inverters	573
Inverters Pnom total	6876 kW AC
Produced Energy	11672 MWh/year
Specific production	1616 kWh/kWp/year
Performance ratio	79.0 %

3) Labor and staff housing. The key results are shown in Table 20. For more results, see appendix C.

Table 20: Output results for Labor and staff housing (Flat PV)

System parameter	Output
Number of PV modules	4160
Pnom total	1040 kWp
Number of inverters	86
Inverters Pnom total	1032 kW AC
Produced Energy	1680 MWh/year
Specific production	1615 kWh/kWp/year
Performance ratio	79.0 %

4) Mosques. The key results are shown in Table 21. For more results, see appendix C.

Table 21: Output results for Mosques (Flat PV)

System parameter	Output
Number of PV modules	2560
Pnom total	640 kWp
Number of inverters	52
Inverters Pnom total	624 kW AC
Produced Energy	1034 MWh/year
Specific production	1615 kWh/kWp/year
Performance ratio	79.0 %

5) Student housing. The key results are shown in Table 22. For more results, see appendix C.

Table 22: Output results for Student housing (Flat PV)

System parameter	Output
Number of PV modules	20400
Pnom total	5100 kWp
Number of inverters	423
Inverters Pnom total	5076 kW AC
Produced Energy	8238 MWh/year
Specific production	1615 kWh/kWp/year
Performance ratio	79.0 %

6) Support facilities. The key results are shown in Table 23. For more results, see appendix C.

Table 23: Output results for Support facilities (Flat PV)

System parameter	Output
Number of PV modules	34000
Pnom total	8500 kWp
Number of inverters	696
Inverters Pnom total	8352 kW AC
Produced Energy	13730 MWh/year
Specific production	1615kWh/kWp/year
Performance ratio	79.0 %

4.5 Cost benefit analysis

As discussed before, the principal concept of BCR analysis is that it integrates the monetary values of the project's gained benefits with its execution costs. The higher the benefit to cost ratio the more beneficial is the project, and consequently, the better the investment.

4.5.1 Gross initial investment calculations

Calculation of the initial investment of the project will take the following costs into consideration (assuming that the installation of the systems will last for two months):

- Cost of PV modules ($150/ module).
- Cost of support and integration ($30/module).
- Cost of inverters ($2700/inverter).
- Cost of setting/ wiring ($4/module).
- Other costs (conveyor, etc.) ($12,000).
- Cost of five unskilled workers for two months ($3000).
- Cost of engineering and technicians ($20,000).
- Note: For mosques and labor & staff housing areas only, the cost of engineering and technicians was assumed $10,000, because only one technician is required since the area is not too large.

Table 24 clarifies the initial investment calculations

Table 24: Initial investment costs calculation.

		Number of modules (PVs)	Cost of modules ($) given ($150/PV)	Cost of support/integration ($30/module)	Number of inverters	Cost of inverters ($) given ($2700/inverter)	Cost of setting/ wiring given ($4/module)	Other costs (conveyor, etc.)($)	Cost of 5 unskilled workers for two months ($)	Cost of engineering and technicians for two months ($)	Total miscellaneous cost ($)	Gross initial investment ($)
PV Tilted 24°	Faculty housing	20,160	**3,024,000**	**604,800**	388	**1,047,600**	**80,640**	12,000	3,000	20,000	35,000	**4,792,040**
	Support facilities	25,500	**3,825,000**	**765,000**	503	**1,358,100**	**102,000**	12,000	3,000	20,000	35,000	**6,085,100**
	Academic buildings	19,200	**2,880,000**	**576,000**	384	**1,036,800**	**76,800**	12,000	3,000	20,000	35,000	**4,604,600**
	Student housing	15,300	**2,295,000**	**459,000**	306	**826,200**	**61,200**	12,000	3,000	20,000	35,000	**3,676,400**
	Labor and staff housing	3,570	**535,500**	**107,100**	71	**191,700**	**14,280**	12,000	3,000	10,000	25,000	**873,580**
	Mosques	2,040	**306,000**	**61,200**	40	**108,000**	**8,160**	12,000	3,000	10,000	25,000	**508,360**
Flat Horizontal PV	Faculty housing	28,900	**4,335,000**	**867,000**	573	**1,547,100**	**115,600**	12,000	3,000	20,000	35,000	**6,899,700**
	Support facilities	34,000	**5,100,000**	**1,020,000**	696	**1,879,200**	**136,000**	12,000	3,000	20,000	35,000	**8,170,200**
	Academic buildings	24,000	**3,600,000**	**720,000**	489	**1,320,300**	**96,000**	12,000	3,000	20,000	35,000	**5,771,300**
	Student housing	20,400	**3,060,000**	**612,000**	423	**1,142,100**	**81,600**	12,000	3,000	20,000	35,000	**4,930,700**
	Labor and staff housing	4,160	**624,000**	**124,800**	86	**232,200**	**16,640**	12,000	3,000	10,000	25,000	**1,022,640**
	Mosques	2,560	**384,000**	**76,800**	52	**140,400**	**10,240**	12,000	3,000	10,000	25,000	**636,440**

Sample calculation for faculty housing (with tilted PV panels):

- Number of modules is 20,160 (from PVsyst software).
- Cost of modules = number of modules × cost of each module

  Cost of modules = 20,160 × 150 = $ 3,024,000.
- Cost of support and integration = number of modules × ($30 / module)

  Cost of support and integration = 20,160 × 30 = $ 604,800.
- Number of inverters is 388 (simulation from PVsyst software).
- Cost of inverters = number of inverters × cost of each inverter
- Cost of inverters = 388 × 2700 = $ 1,047,600.
- Cost of setting and wiring = number of modules × ($4 / module)
- Cost of setting and wiring = 20,160 × 4 = $ 80,640.
- Other costs include the cost conveyor, etc. (it was assumed $ 12,000).
- Cost of five unskilled workers for two months is taken $ 3,000.
- Cost of engineering and technicians ($20,000).
- Total cost of the initial investment is the summation of the above costs

  Total cost of the initial investment = 3,024,000 + 604,800 + 1,047,600 + 80,640 + 12,000 + 3000 + 20,000 = $ 4,792,040.

4.5.2 Operational and maintenance cost calculations

Calculation of the operational and maintenance costs (O&M) of the project will take the following costs into consideration:

- Running costs, maintenance, require two technicians (full time) = $ 8000/month

  = $ 96,000/year.

- Cleaning of solar panels, requires five workers, work 8hr/day. The cleaning is planned to be twice a week. Assuming each worker take $ 4/hour.

  Cleaning cost = 5 worker*((4*8 a day)*2 twice a week*52 weeks in a year) = $ 16,640/ year.

- Total running costs = 96,000+16,640 = $ 112,640/ year.
- Note: For mosques and labor & staff housing areas only, assume that one full time technician is required, $ 48,000/year. This will make the O&M costs for these areas = 48,000+16640 = $ 64,640/year.

All details are shown in Table 25 below.

Table 25: Annual total O&M costs.

		Maintenance, technician given($4000/month). ($/year)	Cleaning, 5 workers 8hrs/day, twice a week. ($/year)	Total Operation & Maintenance cost ($/year)
PV Tilted 24°	Faculty housing	96,000	16,640	**112,640**
	Support facilities	96,000	16,640	**112,640**
	Academic buildings	96,000	16,640	**112,640**
	Student housing	96,000	16,640	**112,640**
	Labor and staff housing	48,000	16,640	**64,640**
	Mosques	48,000	16,640	**64,640**
Flat Horizontal PV	Faculty housing	96,000	16,640	**112,640**
	Support facilities	96,000	16,640	**112,640**
	Academic buildings	96,000	16,640	**112,640**
	Student housing	96,000	16,640	**112,640**
	Labor and staff housing	48,000	16,640	**64,640**
	Mosques	48,000	16,640	**64,640**

4.5.3 Benefit - cost calculation

4.5.3.1 Net present value calculations

The project life cycle is twenty-five years. Inverters were assumed to be replaced every eight years. The cost of inverters will have a discount rate in the feature of 4% per year (Rehman, 2006). The cost of replacing invertors will be converted to the NPV, and then will be converted again to be distributed as annual costs. These costs will be added to the original O&M costs. Table 26 addresses the costs of inverters replacements. Figure 50 shows the schematic cash flow diagram for the rooftop PV systems.

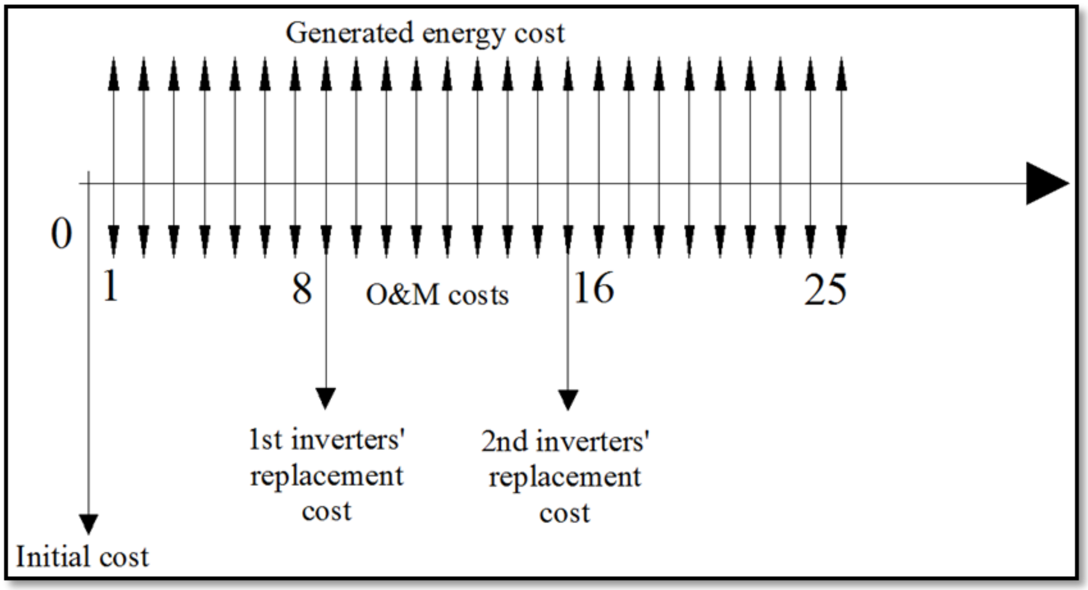


Figure 50: Cash flow diagram for rooftop PV systems

Assumptions:

- The project life cycle is 25 years.
- Interest rate is 2%.
- Inverter replacement is at year 8 and year 16 of the project life.
- Inverter replacement costs will be calculated and converted to annual costs. Then they will be added the total annual maintenance and operational costs.
- Operational and maintenance costs are taken annually.
- Generated energy costs are taken annually.

The net present value (NPV) of the costs can be calculated as:

$$NPV = P_0 + O\&M\ (P/A, 2\%, 25) + 1st\ replacement\ (P/F, 2\%, 8) + 2nd\ replacement\ (P/F, 2\%, 16)$$

Table 26: Inverters replacement calculations

		Initial investment ($)	Annual O&M ($/year)	NPV of O&M ($)	Number of inverters	Cost of inverters ($)	Inverter discount rate (%/year)	Cost of First replacement of inverters after 8 years ($)	NPV of first replacement ($)	Cost of Second replacement of inverters after 16 years ($)	NPV of second replacement ($)
PV Tilted 24°	Faculty housing	**4,792,040**	112,640	**2,199,127**	388	1,047,600	4%	712,368	**608,006**	377,136	**274,706**
	Support facilities	**6,085,100**	112,640	**2,199,127**	503	1,358,100	4%	923,508	**788,214**	488,916	**356,126**
	Academic buildings	**4,604,600**	112,640	**2,199,127**	384	1,036,800	4%	705,024	**601,738**	373,248	**271,874**
	Student housing	**3,676,400**	112,640	**2,199,127**	306	826,200	4%	561,816	**479,510**	297,432	**216,649**
	Labor and staff housing	**873,580**	64,649	**1,262,175**	71	191,700	4%	130,356	**111,259**	69,012	**50,268**
	Mosques	**508,360**	64,649	**1,262,175**	40	108,000	4%	73,440	**62,681**	38,880	**28,320**
Flat Horizontal PV	Faculty housing	**6,899,700**	112,640	**2,199,127**	573	1,547,100	4%	1,052,028	**897,906**	556,956	**405,687**
	Support facilities	**8,170,200**	112,640	**2,199,127**	696	1,879,200	4%	1,277,856	**1,090,650**	676,512	**492,771**
	Academic buildings	**5,771,300**	112,640	**2,199,127**	489	1,320,300	4%	897,804	**766,276**	475,308	**346,214**
	Student housing	**4,930,700**	112,640	**2,199,127**	423	1,142,100	4%	776,628	**662,852**	411,156	**299,486**
	Labor and staff housing	**1,022,640**	64,640	**1,261,999**	86	232,200	4%	157,896	**134,764**	83,592	**60,888**
	Mosques	**636,440**	64,640	**1,261,999**	52	140,400	4%	95,472	**81,485**	50,544	**36,816**

4.5.3.2 Annual cost calculations

The total NPV of all costs are found. Then, the NPV panels will be converted to annual costs to find the cost for each year during the project life cycle. See Table 27.

$$Annual\ cost = NPV\ (A/P, 2\%, 25)$$

Table 27: NPV to annual cost calculations

		Initial investment ($)	NPV of O&M ($)	NPV of first replacement ($)	NPV of second replacement ($)	Total NPV ($)	Annual Cost ($/year)
PV Tilted 24°	Faculty housing	**4,792,040**	**2,199,127**	**608,006**	**274,706**	**7,873,879**	**403,300**
	Support facilities	**6,085,100**	**2,199,127**	**788,214**	**356,126**	**9,428,568**	**482,931**
	Academic buildings	**4,604,600**	**2,199,127**	**601,738**	**271,874**	**7,677,339**	**393,233**
	Student housing	**3,676,400**	**2,199,127**	**479,510**	**216,649**	**6,571,686**	**336,602**
	Labor and staff housing	**873,580**	**1,262,175**	**111,259**	**50,268**	**2,297,282**	**117,667**
	Mosques	**508,360**	**1,262,175**	**62,681**	**28,320**	**1,861,536**	**95,348**
Flat Horizontal PV	Faculty housing	**6,899,700**	**2,199,127**	**897,906**	**405,687**	**10,402,420**	**532,812**
	Support facilities	**8,170,200**	**2,199,127**	**1,090,650**	**492,771**	**11,952,748**	**612,220**
	Academic buildings	**5,771,300**	**2,199,127**	**766,276**	**346,214**	**9,082,917**	**465,227**
	Student housing	**4,930,700**	**2,199,127**	**662,852**	**299,486**	**8,092,165**	**414,481**
	Labor and staff housing	**1,022,640**	**1,261,999**	**134,764**	**60,888**	**2,480,292**	**127,041**
	Mosques	**636,440**	**1,261,999**	**81,485**	**36,816**	**2,016,741**	**103,297**

4.5.3.3 Benefit to cost ratio calculations

Knowing the annual energy generation from each area category, will make it easy to calculate the annual benefits in terms of monetary values. Given that, the price of 1MWh of electricity is equal to $69.32. Finally, the benefit to cost ratio can be easily calculated.

Table 28 shows all the calculations for all cases.

Table 28: Benefit to cost ratio calculation

		Produced Energy (MWh/year)	SR 260 = $ 69.32 Benefit or Cost of Produced Energy ($/year)	Annual Cost ($/year)	(Benefit/Cost) ratio, annual
PV Tilted 24˚	Faculty housing	8871	**614,938**	**403,300**	**1.52**
	Support facilities	11223	**777,978**	**482,931**	**1.61**
	Academic buildings	8450	**585,754**	**393,233**	**1.49**
	Student housing	6733	**466,732**	**336,602**	**1.39**
	Labor and staff housing	1571	**108,902**	**117,667**	**0.93**
	Mosques	897.9	**62,242**	**95,348**	**0.65**
Flat Horizontal PV	Faculty housing	11672	**809,103**	**532,812**	**1.52**
	Support facilities	13730	**951,764**	**612,220**	**1.55**
	Academic buildings	9693	**671,919**	**465,227**	**1.44**
	Student housing	8238	**571,058**	**414,481**	**1.38**
	Labor and staff housing	1680	**116,458**	**127,041**	**0.92**
	Mosques	1034	**71,677**	**103,297**	**0.69**

Figure 51, Figure 52, and Figure 53 show the benefit to cost ratio for all the areas in KFUPM.

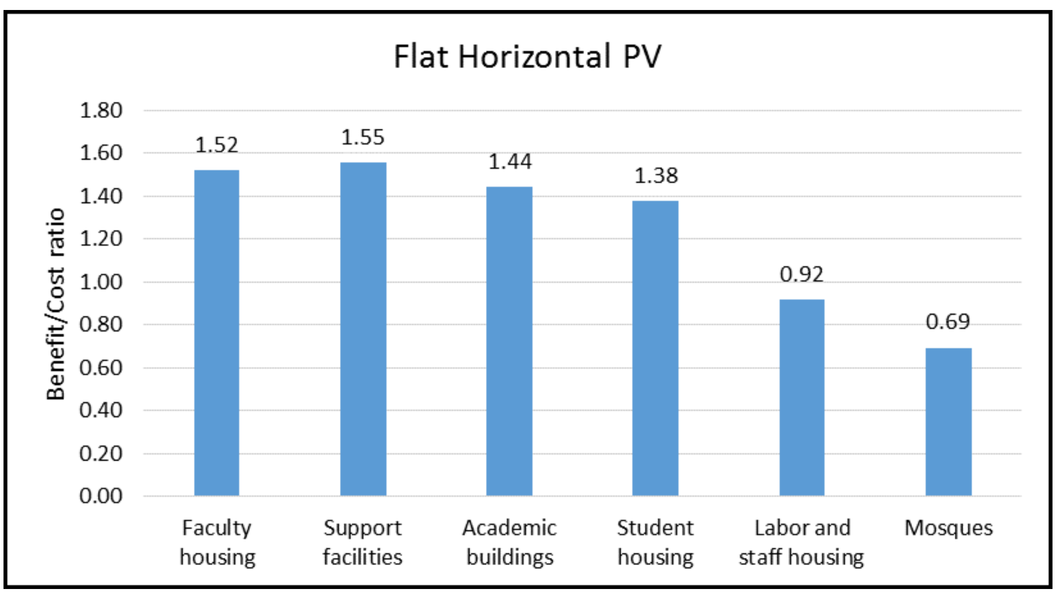


Figure 51: Benefit to cost ratio for flat PV panels

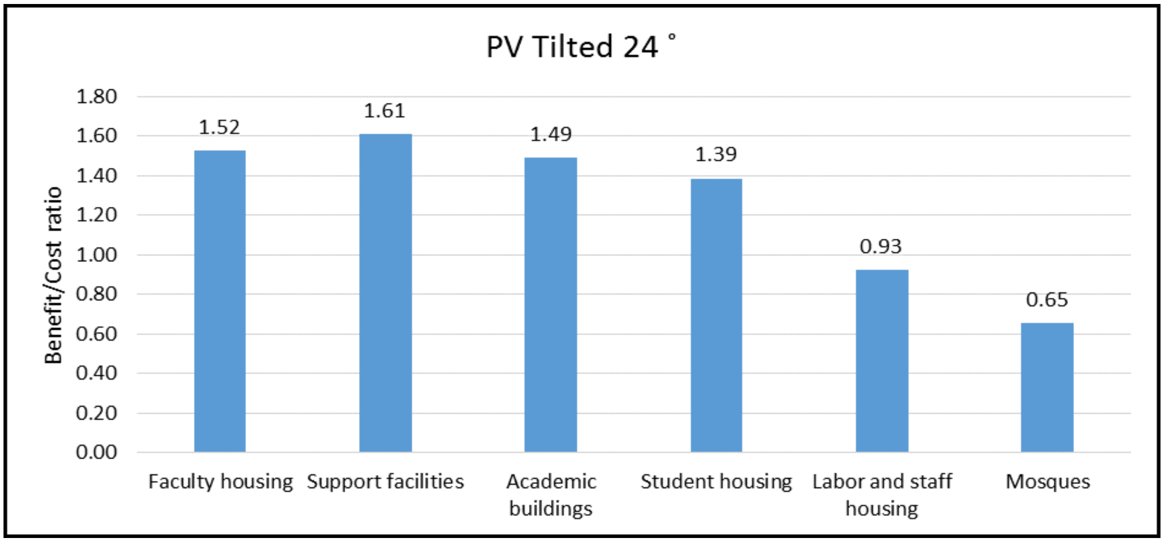


Figure 52: Benefit to cost ratio for tilted PV panels

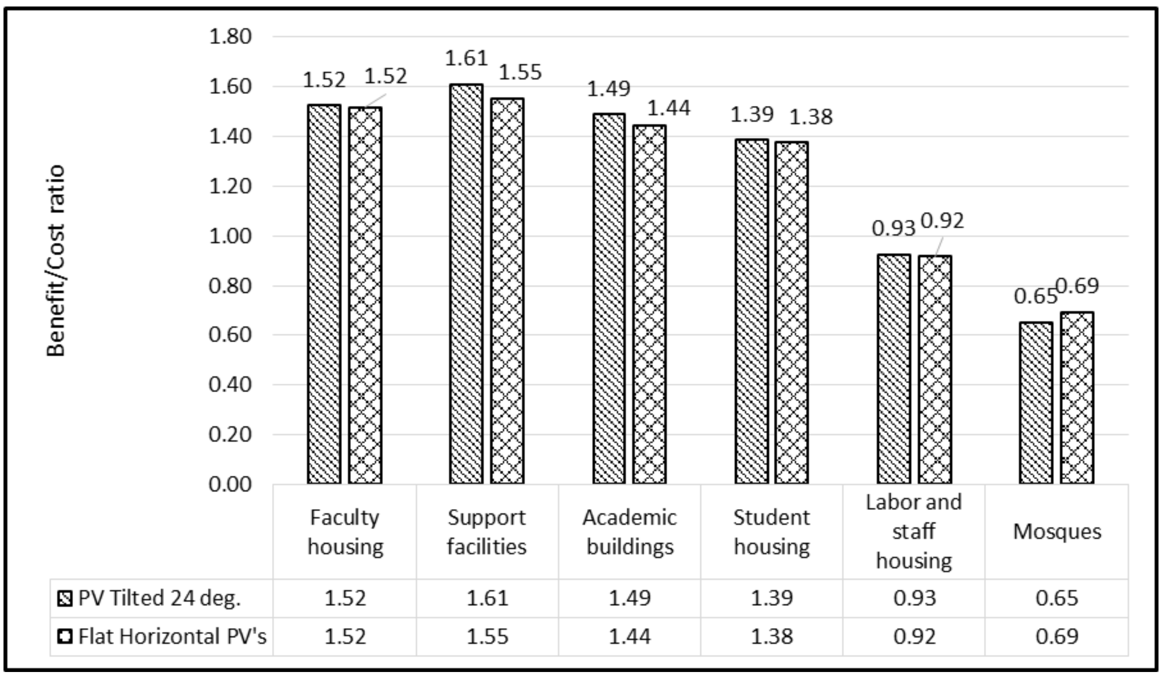


Figure 53: Combined Benefit to cost ratio for tilted and flat PV panels

It can be noticed that the tilted PV panels have slightly higher benefit to cost ratio than the flat PV panels, this is because that the tilted PV panels cover less roof area to avoid the shading between panels on each other, and thus offer less initial costs compared with horizontal PV panels. Also, the BCR is higher than 1 for all the areas except for labor & staff housing, and mosques. This indicates that these areas will be beneficial if they are invested with solar PV projects. The higher BCR is for the support facilities, then faculty housing, academic buildings, and student housing.

4.5.4 Cash flows and simple payback periods

Following is the cash flows for all the KFUPM's buildings and for the two cases of PV installation. The cash flows were developed by the use of RETScreen software. The software also calculates the simple payback periods and equity periods.

- Simple payback period (SPP) represents the length of time that it takes for a proposed project to recoup its own initial cost, out of the income or savings it generates. The simple payback should not be used as the primary indicator to evaluate a project. It is useful, however, as a secondary indicator to indicate the level of risk of an investment. A further criticism of the simple payback method is that it does not consider the time value of money, nor the impact of inflation on the costs.
- The equity payback period represents the length of time that it takes for the owner of a project to recoup its own initial investment (equity) out of the project cash flows generated. The equity payback considers project cash flows from its inception as well as the leverage (level of debt) of the project, which makes it a better time indicator of the project merits than the simple payback. Sometimes, the equity period is called "years to positive cash flow (YPCF)".

4.5.4.1 Tilted PV panels

All the cash flow diagrams for the tilted PV solar systems are shown in Figure 54, Figure 55, Figure 56, Figure 57, Figure 58, and Figure 59. Note that the inverter replacement is at year 8 and year 16 of the project life. The inverter replacement costs will be calculated and converted to annual costs. Then they will be added the total annual maintenance and operational costs.

- Academic buildings. SPP= 10.8 years. Equity payback= 9.7 years.

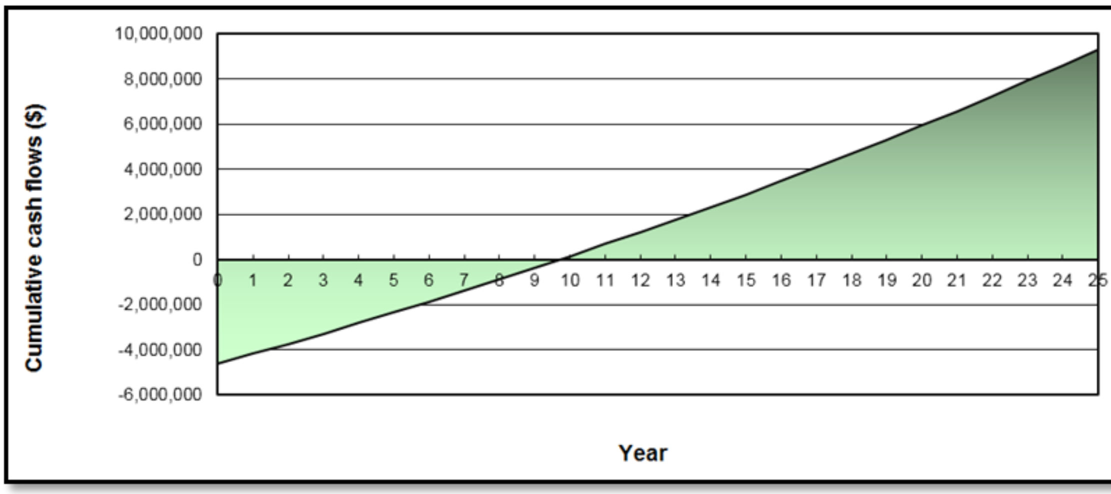


Figure 54: Cash flow diagram for Academic buildings (Tilted PV panels) (Source: RETScreen)

- Faculty housing. SPP= 10.5 years, equity payback= 9.5 years.

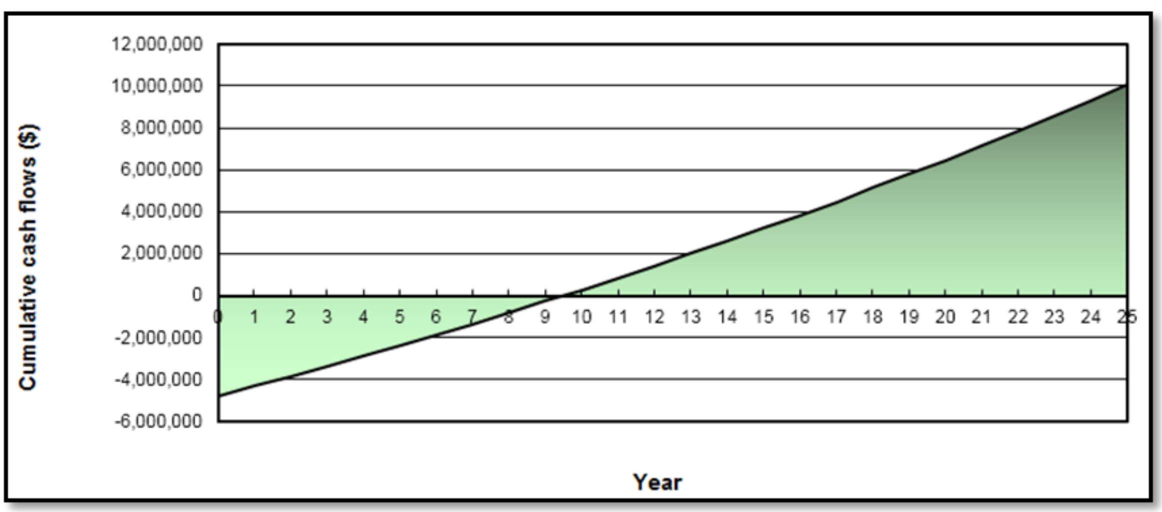


Figure 55: Cash flow diagram for Faculty housing (Tilted PV panels) (Source: RETScreen)

- Labor and staff housing SPP= 24.6 years, equity payback= 19.9 years.

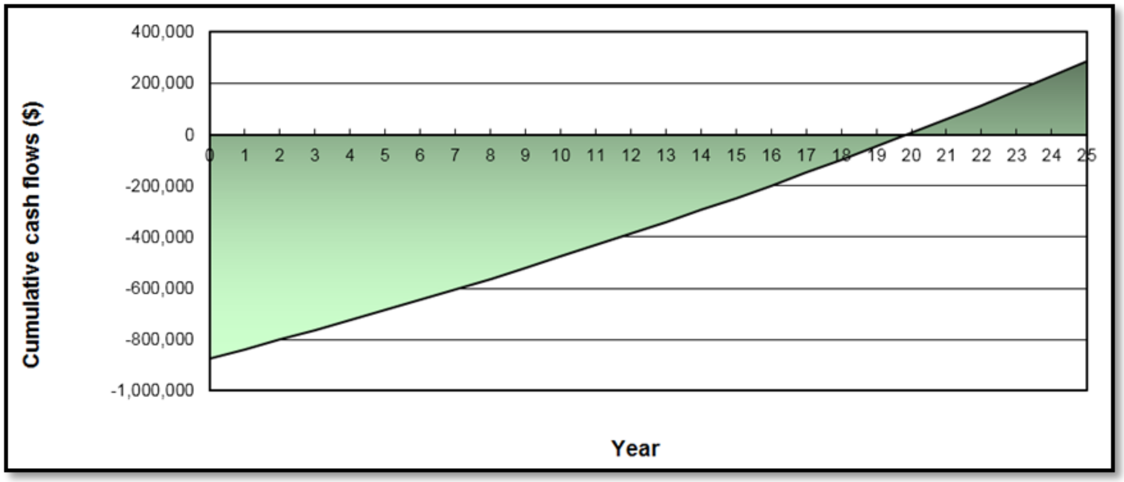


Figure 56: Cash flow diagram for labor & staff housing (Tilted PV panels) (Source: RETScreen)

- Mosques SPP= NA, equity payback= NA.

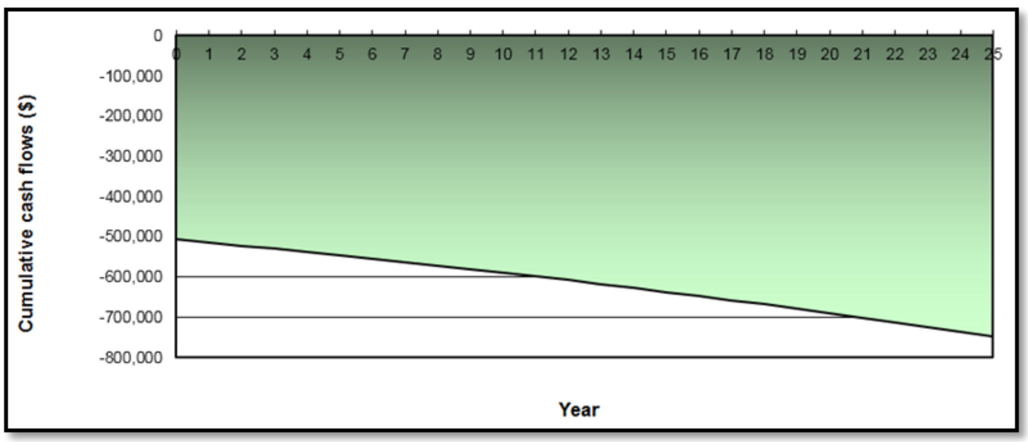


Figure 57: Cash flow diagram for mosques (Tilted PV panels) (Source: RETScreen)

- Student housing SPP= 11.6 years, equity payback= 10.4 years.

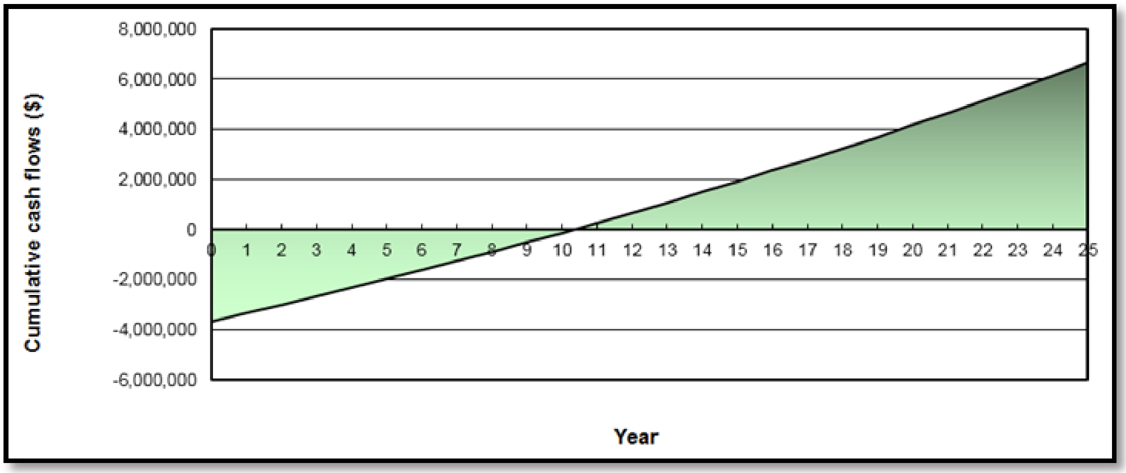


Figure 58: Cash flow diagram for student housing (Tilted PV panels) (Source: RETScreen)

- Support facilities SPP= 10.1 years, equity payback= 9.1 years.

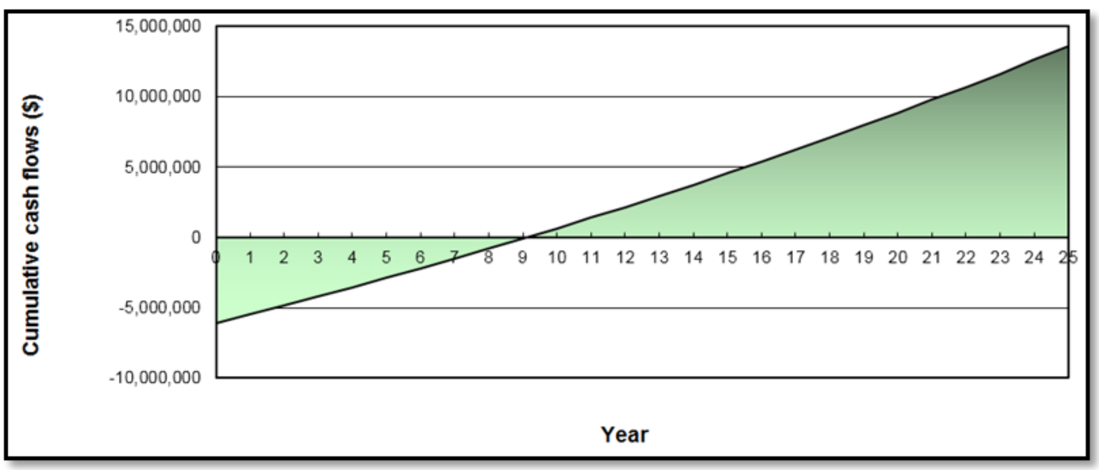


Figure 59: Cash flow diagram for support facilities (Tilted PV panels) (Source: RETScreen)

4.5.4.2 Flat or horizontal PV panels

All the cash flow diagrams for the tilted PV solar systems are shown in Figure 60, Figure 61, Figure 62, Figure 63, Figure 64, and Figure 65.

- Academic buildings SPP= 10.1 years, equity payback= 9.1 years.

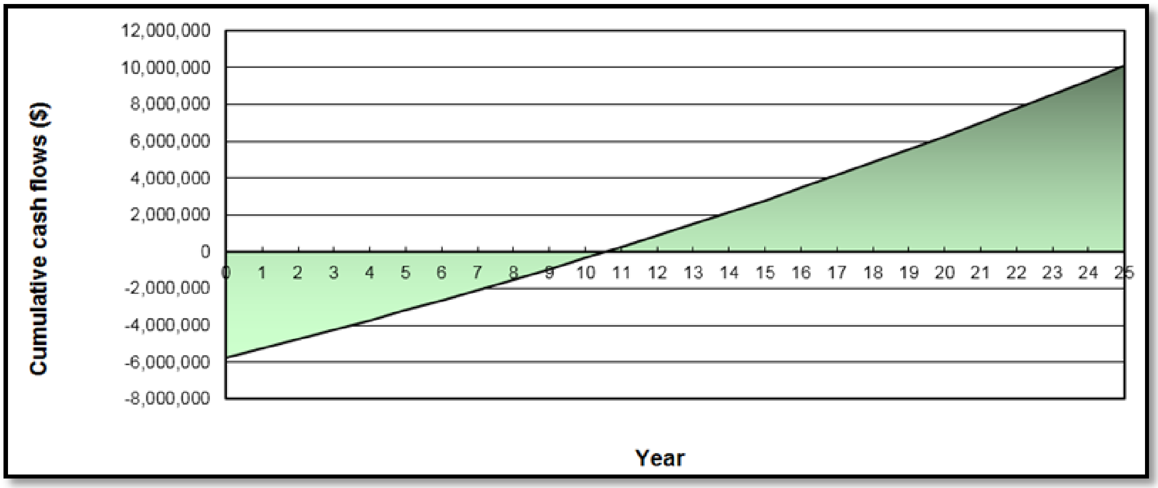


Figure 60: Cash flow diagram for Academic buildings (Flat PV panels) (Source: RETScreen)

- Faculty housing SPP= 11.3 years, equity payback= 10.1 years.

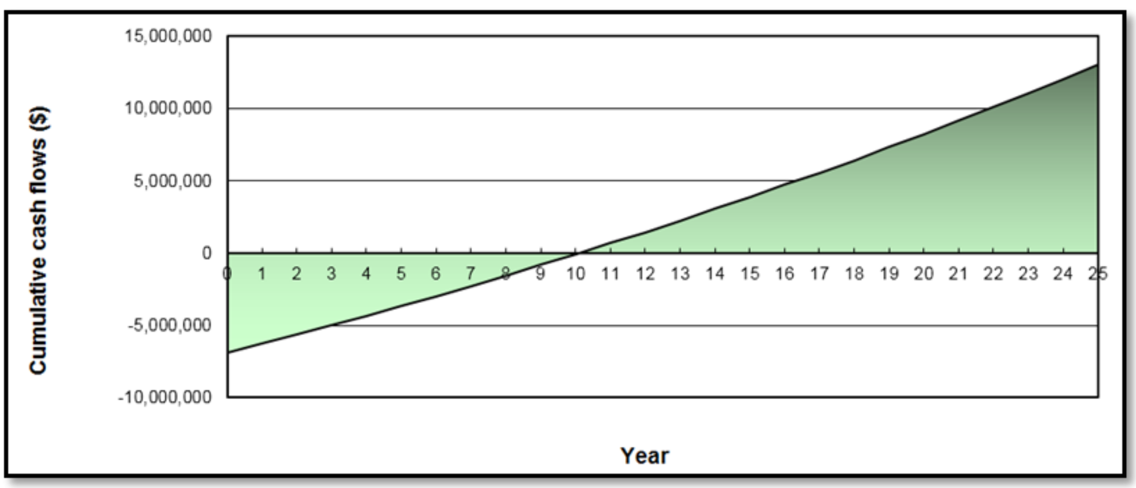


Figure 61: Cash flow diagram for Faculty housing (Flat PV panels) (Source: RETScreen)

- Labor and staff housing SPP= 26.2 years, equity payback= 20.9 years.

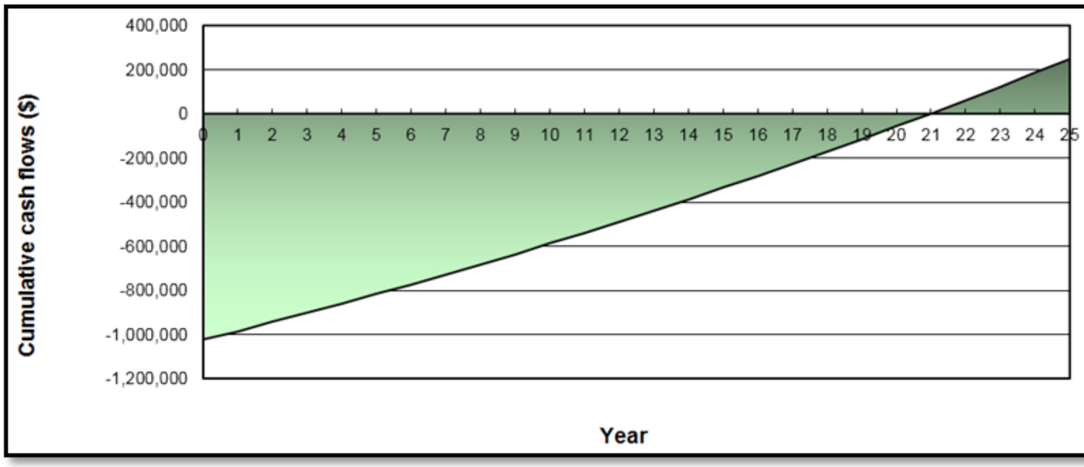


Figure 62: Cash flow diagram for labor & staff housing (Flat PV panels) (Source: RETScreen)

- Mosques SPP= NA, equity payback= NA.

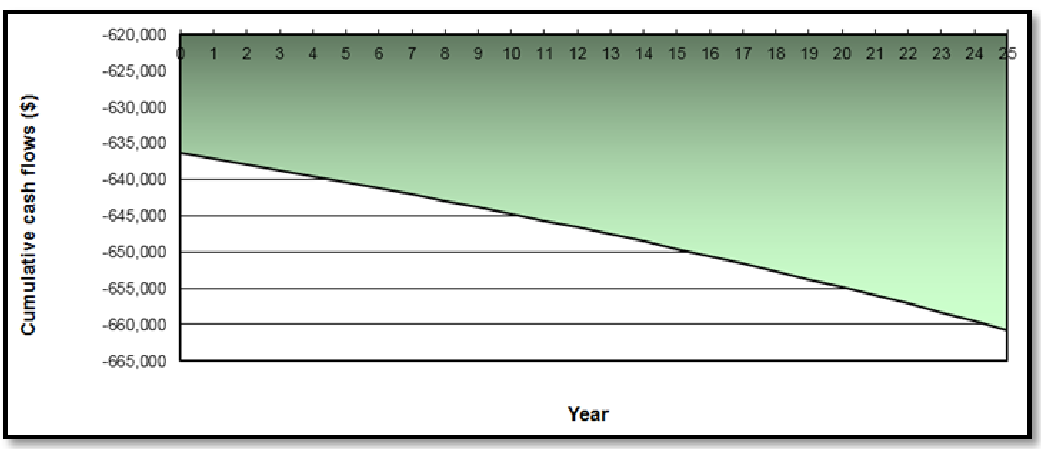


Figure 63: Cash flow diagram for mosques (Flat PV panels) (Source: RETScreen)

- Student housing SPP= 12.5 years, equity payback= 11.0 years.

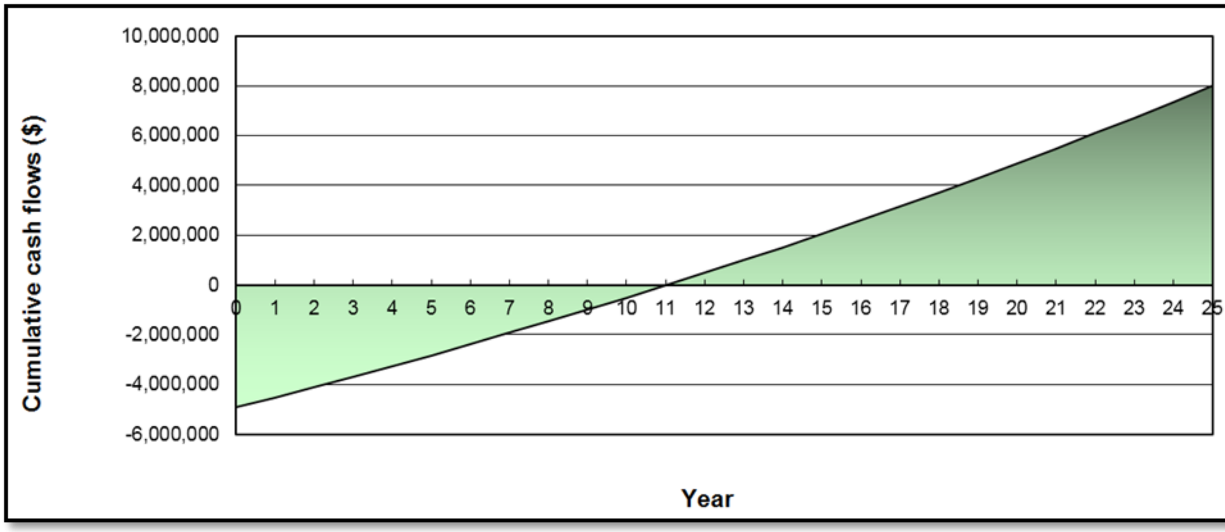


Figure 64: Cash flow diagram for student housing (Flat PV panels) (Source: RETScreen)

- Support facilities SPP= 11.1 years, equity payback= 10.0 years.

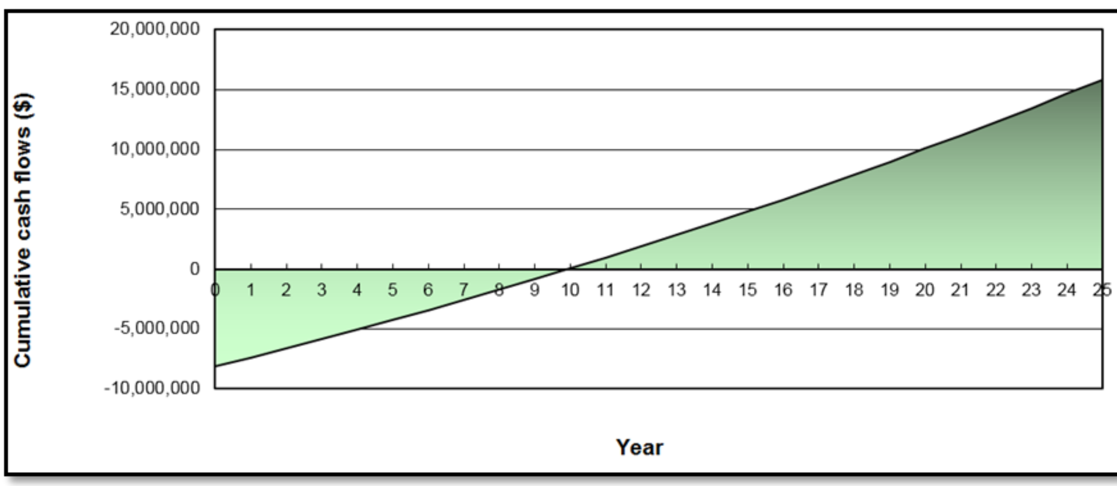


Figure 65: Cash flow diagram for support facilities (Flat PV panels) (Source: RETScreen)

All the previous results of the benefit to cost ratio (BCR), simple payback period (SPP), and equity periods are summarized in Table 29. It can be noticed that the average of the simple payback periods for the investment in tilted PV panels is 13.5 years (excluding mosques which showed neither SPP nor equity periods in all cases). Whereas, the average of equity periods is 11.7 years. On the other hand, the investment in horizontal flat PV panels has slightly longer periods, the average of simple payback periods is 14.2 years and the average of the equity periods is 12.2 year.

Table 29: Summary of SPP and equity periods for the investment in KFUPM

	PV Tilted 24°			Flat Horizontal PV		
Area category	**SPP (years)**	**Equity period (years)**	**BCR**	**SPP (years)**	**Equity period (years)**	**BCR**
Academic buildings	10.8	9.7	1.49	10.1	9.1	1.44
Faculty housing	10.5	9.5	1.52	11.3	10.1	1.52
Labor and staff housing	24.6	19.9	0.93	26.2	20.9	0.92
Mosques	NA	NA	0.65	NA	NA	0.69
Student housing	11.6	10.4	1.39	12.5	11.0	1.38
Support facilities	10.1	9.1	1.61	11.1	10.0	1.55
Average	**13.5**	**11.7**	**1.27**	**14.2**	**12.2**	**1.25**

4.6 GHG reduction

For the environmental analysis, the greenhouse gases (GHG): carbon dioxide, methane, and nitrous oxide will be calculated and estimated. The energy mix for Saudi Arabia was determined; electricity generation is 65% from Oil, 27% from Natural Gas. The emission factors were taken from (U.S. Energy Information Administration reports, 2014). Table 30 shows these emissions factors and the amount of GHG emission inventory and emission reductions. These gases include:

1- Carbon dioxide, the conversion factor is 0.816 (Metric tons/MWh).

2- Methane, the conversion factor is 0.02678 (kg/ MWh).

3- Nitrous oxide, the conversion factor is 0.00487 (kg /MWh).

Table 30: GHG emissions

			Emission Inventory [a]			Emission Reductions	
	Region/Country	Produced Energy (MWh/year)	Carbon Dioxide (Metric tons/MWh)	Methane (kg/ MWh)	Nitrous Oxide (kg/ MWh)	Avoided Emissions [b] (Metric tons CO2e/MWh)	Indirect Emissions [c] (Metric tons CO2e/MWh)
	Saudi Arabia		**0.816**	**0.02678**	**0.00487**	**0.818**	**0.873**
PV Tilted 24°	Faculty housing	8,871	7,239	238	43	7,256	7,744
	Support facilities	11,223	9,158	301	55	9,180	9,798
	Academic buildings	8,450	6,895	226	41	6,912	7,377
	Student housing	6,733	5,494	180	33	5,508	5,878
	Labor and staff housing	1,571	1,282	42	8	1,285	1,371
	Mosques	898	733	24	4	734	784
Flat Horizontal PV	Faculty housing	11,672	9,524	313	57	9,548	10,190
	Support facilities	13,730	11,204	368	67	11,231	11,986
	Academic buildings	9,693	7,909	260	47	7,929	8,462
	Student housing	8,238	6,722	221	40	6,739	7,192
	Labor and staff housing	1,680	1,371	45	8	1,374	1,467
	Mosques	1,034	844	28	5	846	903

Where:

(a) Emission inventory electricity emission factors are based on average emissions intensity of total electric sector generation for specified countries or country-based regions and include transmission and distribution (T&D) losses incurred in delivering electricity to the point of use.

(b) Avoided emissions benchmark emission factors are based on average emissions intensity of fossil-fired generation for specified countries or country-based regions, but do not exceed 0.9 metric tons CO2e per MWh. Note that the Avoided emissions benchmarks do not include (T&D) losses.

(c) Indirect emission reductions emission factors for reduced purchases of electricity are based on average emissions intensity of fossil-fired generation for specified countries or country-based regions and include transmission and distribution (T&D) losses incurred in delivering electricity to point of use.

The produced energy from tilted and flat PV panels are shown in Figure 66, Figure 67, and Figure 68.

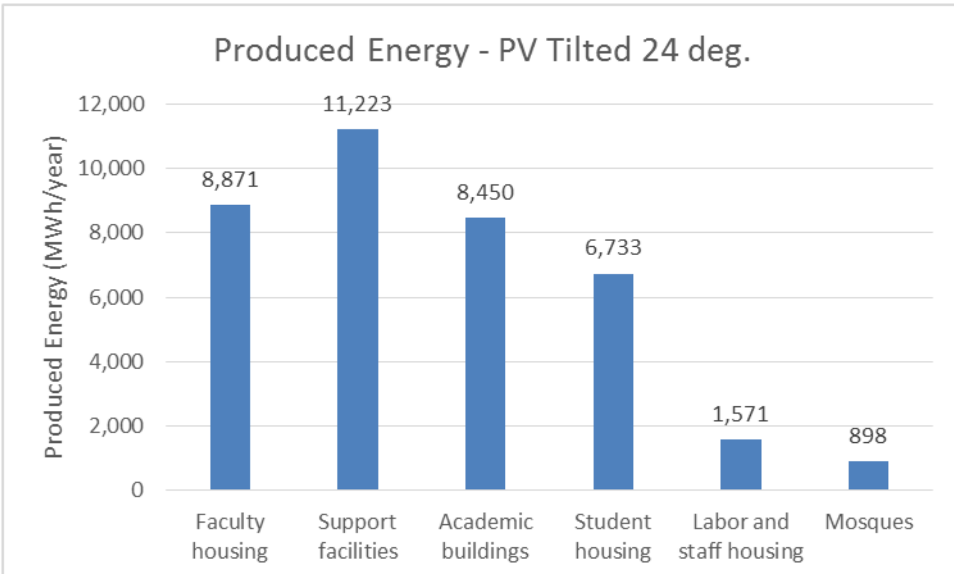


Figure 66: Produced Energy - PV Tilted 24°

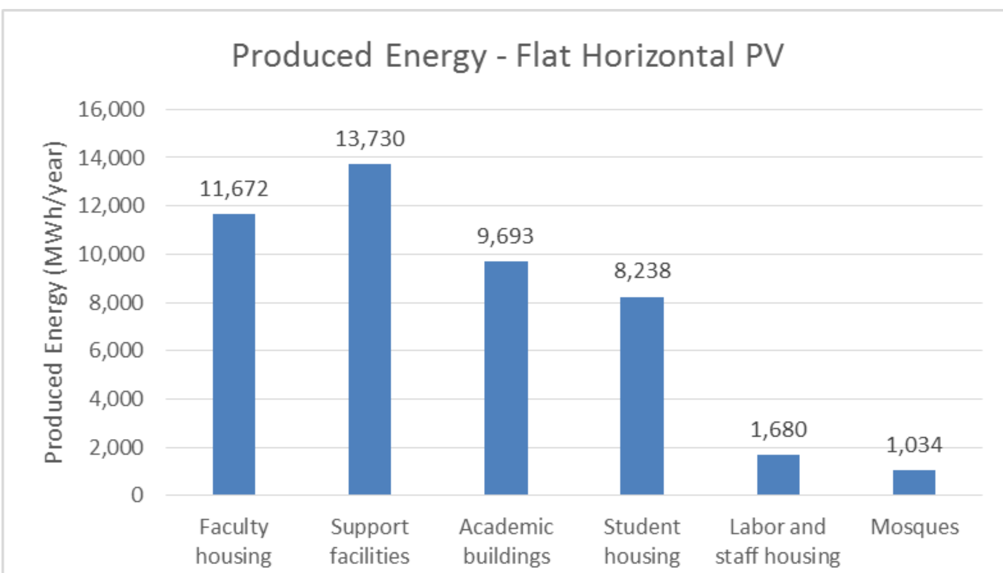
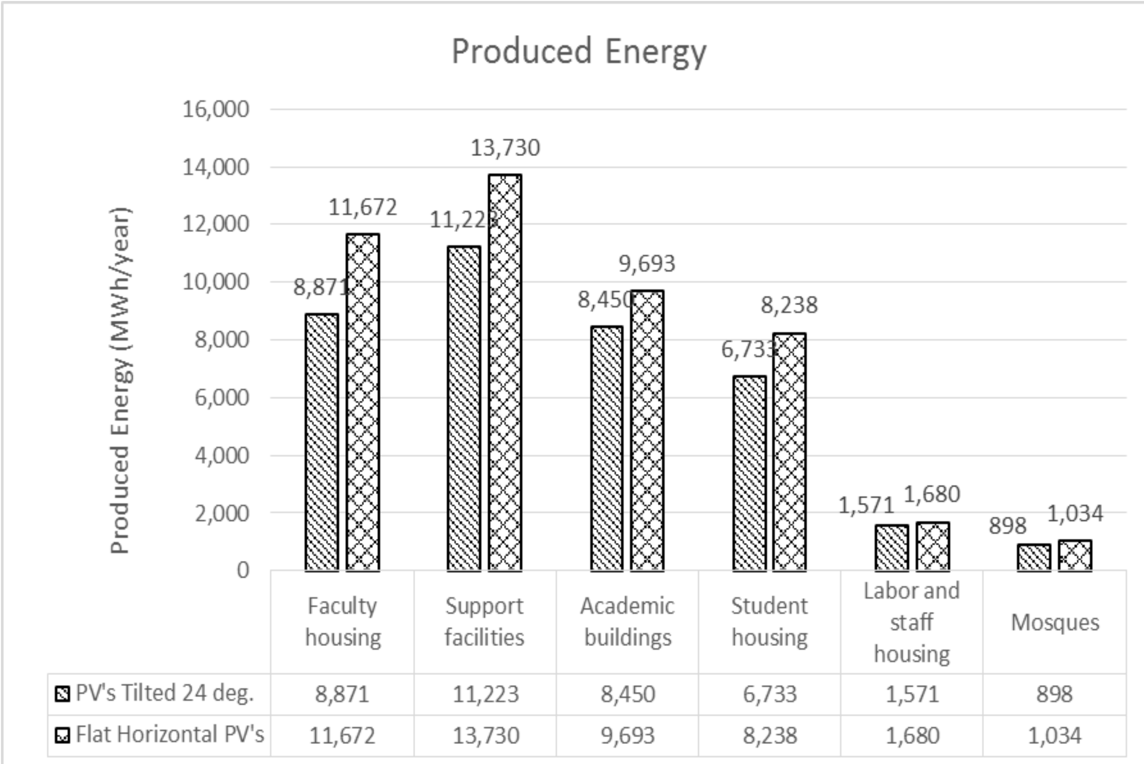


Figure 67: Produced Energy - Flat Horizontal PV



	Faculty housing	Support facilities	Academic buildings	Student housing	Labor and staff housing	Mosques
PV's Tilted 24 deg.	8,871	11,223	8,450	6,733	1,571	898
Flat Horizontal PV's	11,672	13,730	9,693	8,238	1,680	1,034

Figure 68: Combined Produced Energy from Flat and Tilted PV panels

Carbon Dioxide Emissions are shown in Figure 69, Figure 70, and Figure 71.

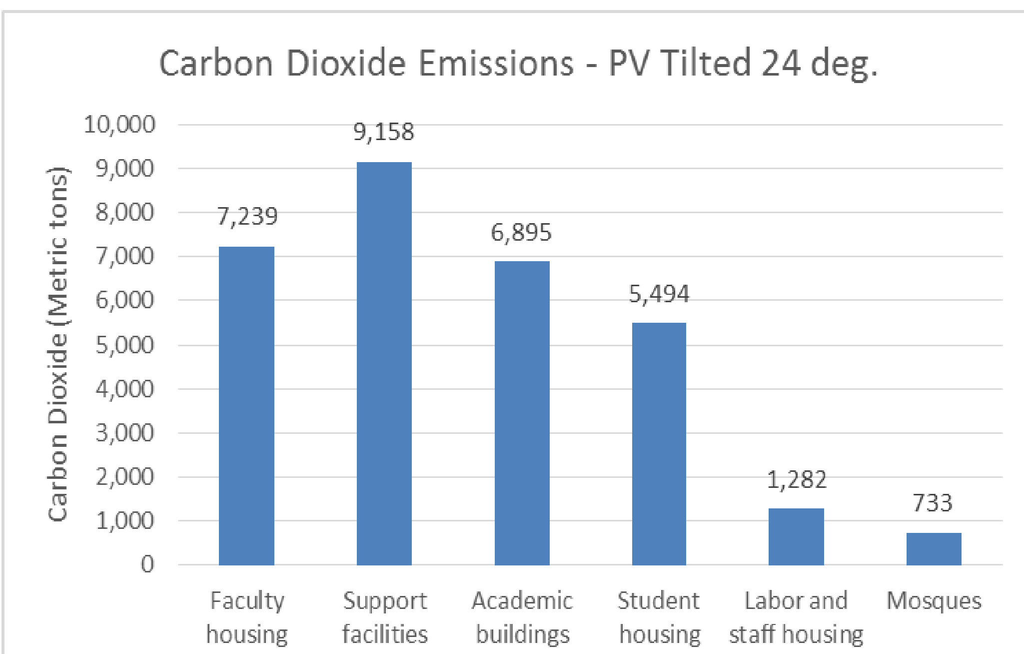


Figure 69: Carbon Dioxide Emissions - PV Tilted 24°

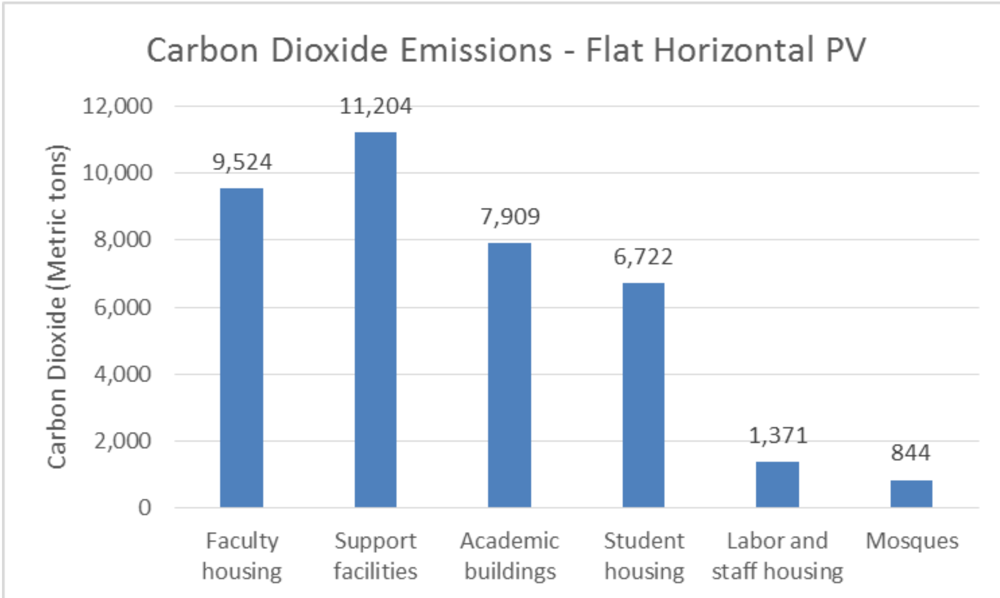


Figure 70: Carbon Dioxide Emissions - Flat Horizontal PV

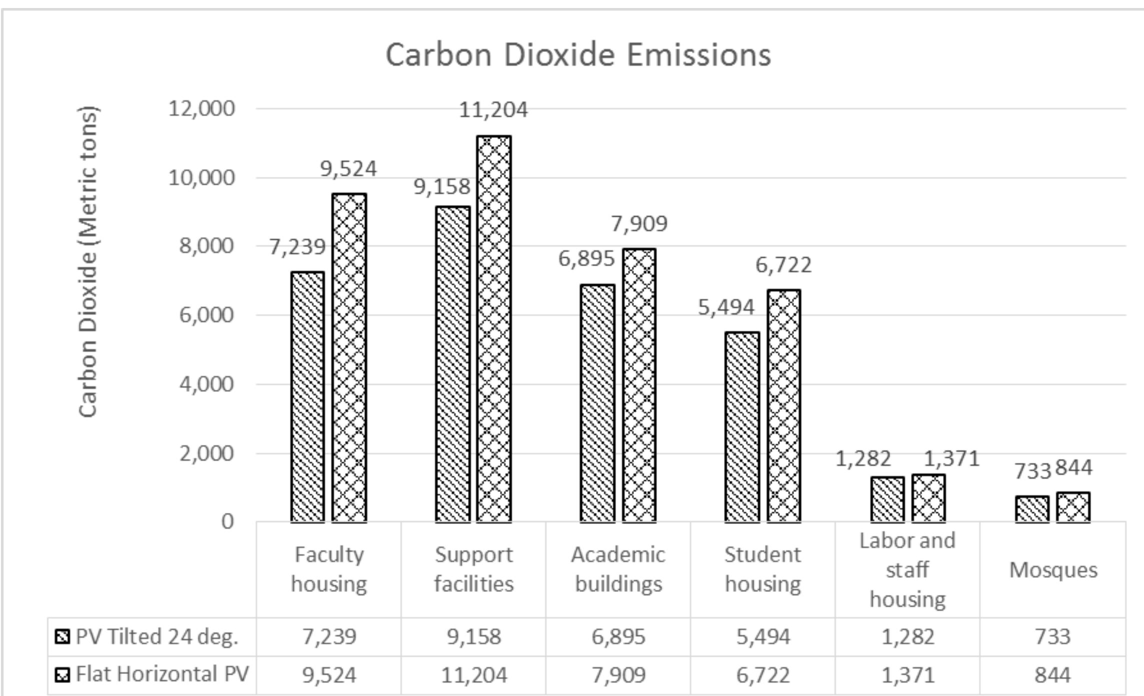


Figure 71: Carbon Dioxide Emissions from flat and tilted PV panels

Methane emissions are shown in Figure 72, Figure 73, and Figure 74.

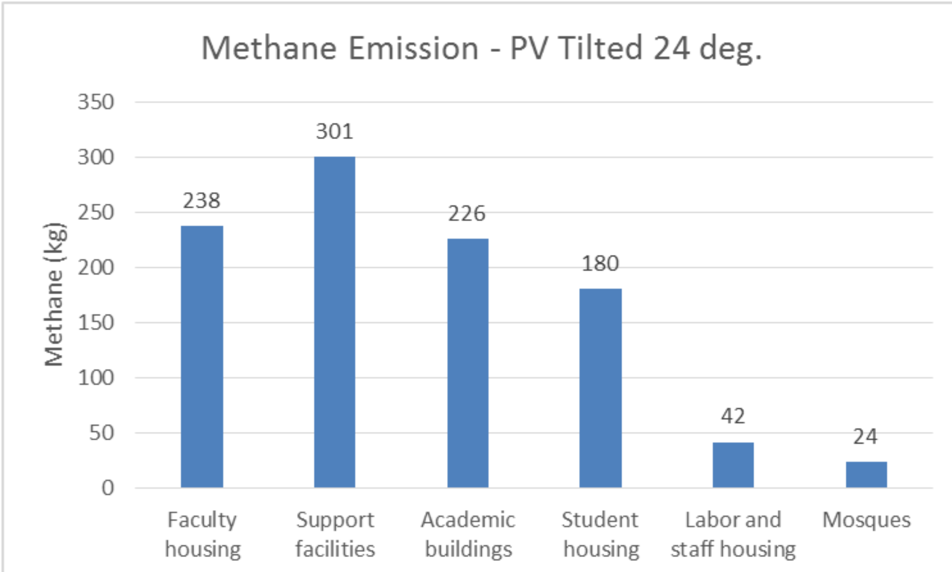


Figure 72: Methane Emission - PV Tilted 24°

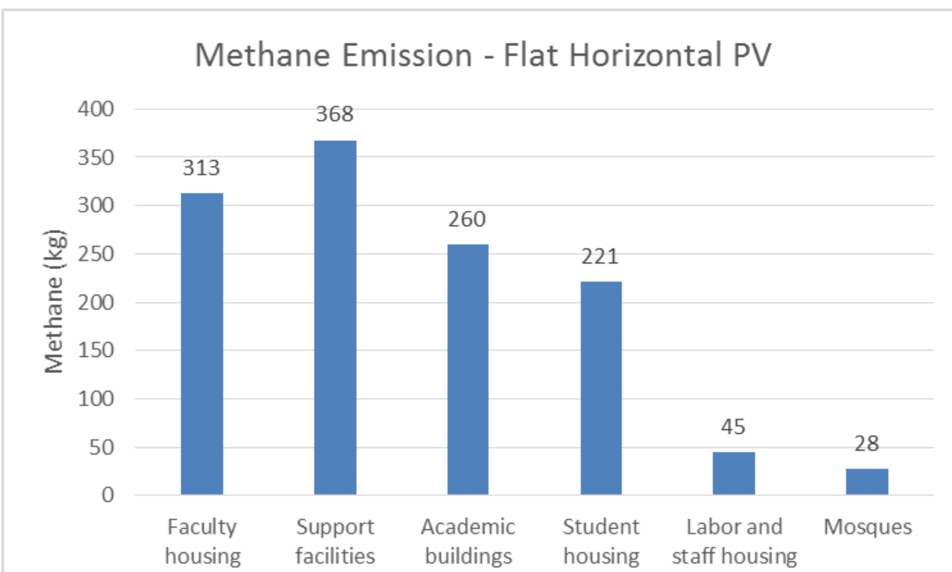


Figure 73: Methane Emission - Flat Horizontal PV

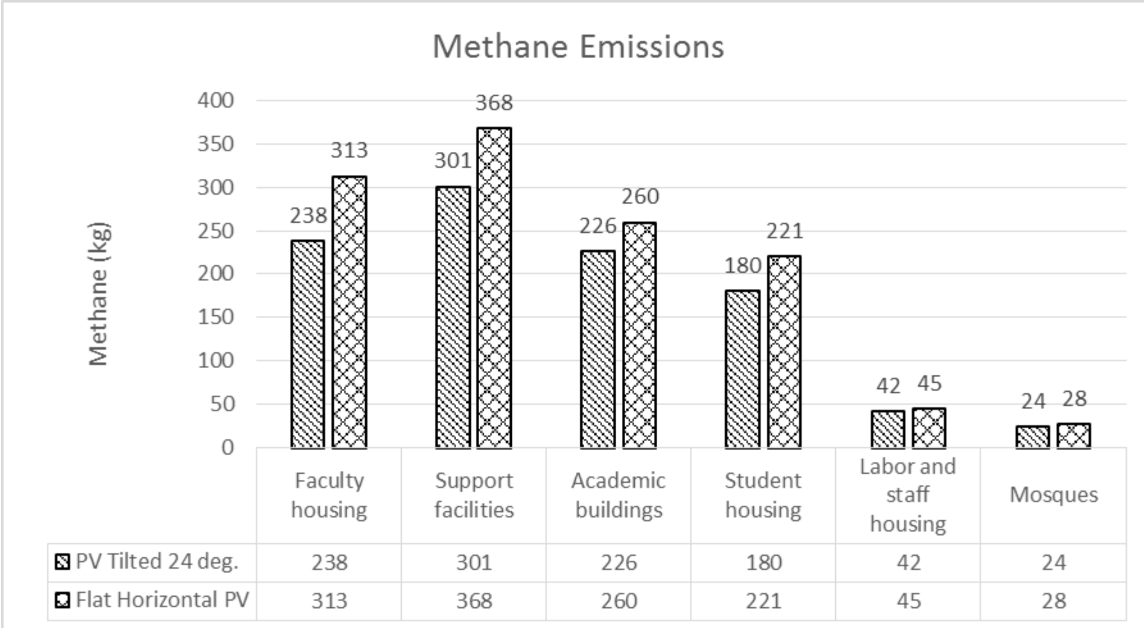


Figure 74: Methane Emission from Flat and Tilted PV panels

Nitrous Oxide emissions are shown in Figure 75, Figure 76, and Figure 77.

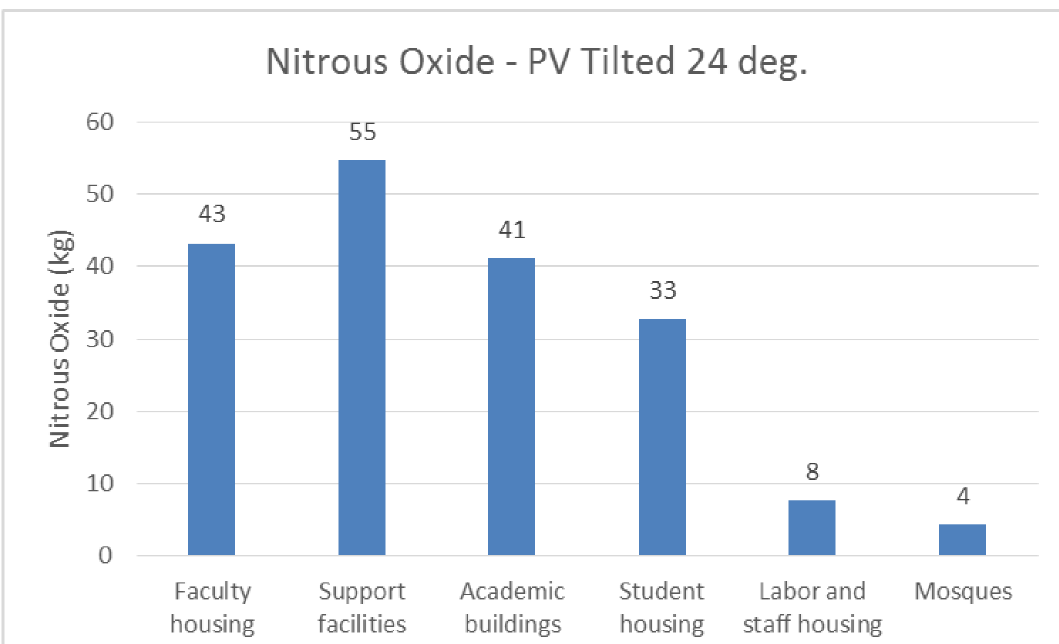


Figure 75: Nitrous Oxide - PV Tilted 24°

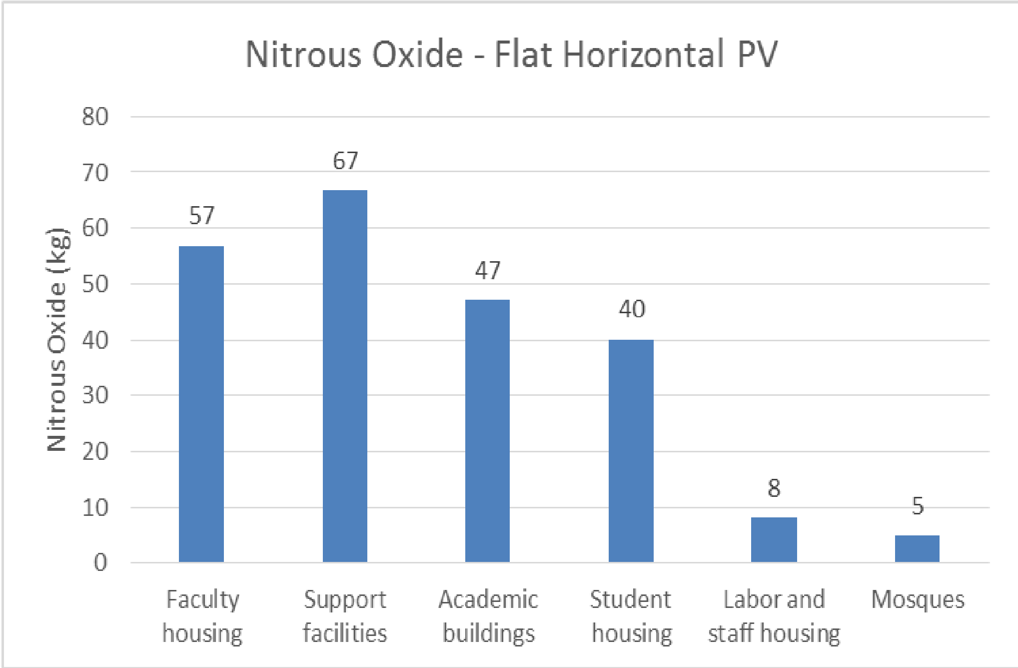


Figure 76: Nitrous Oxide - Flat Horizontal PV

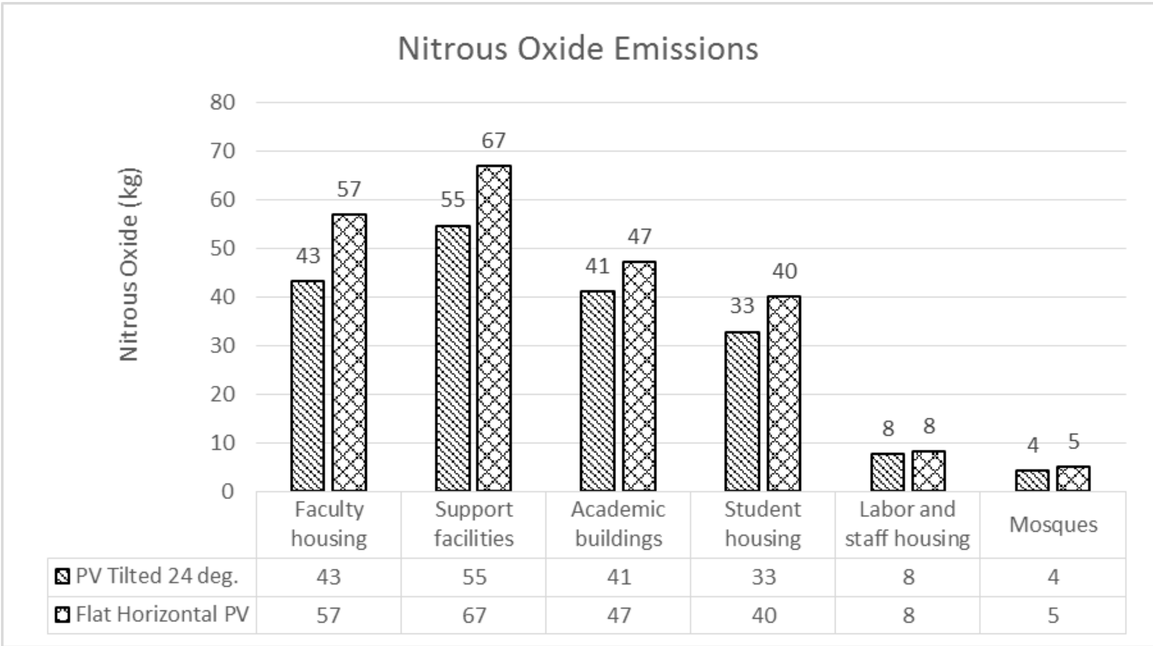


Figure 77: Nitrous Oxide from Flat and Tilted PV panels

The avoided emissions are shown in Figure 78, Figure 79, and Figure 80.

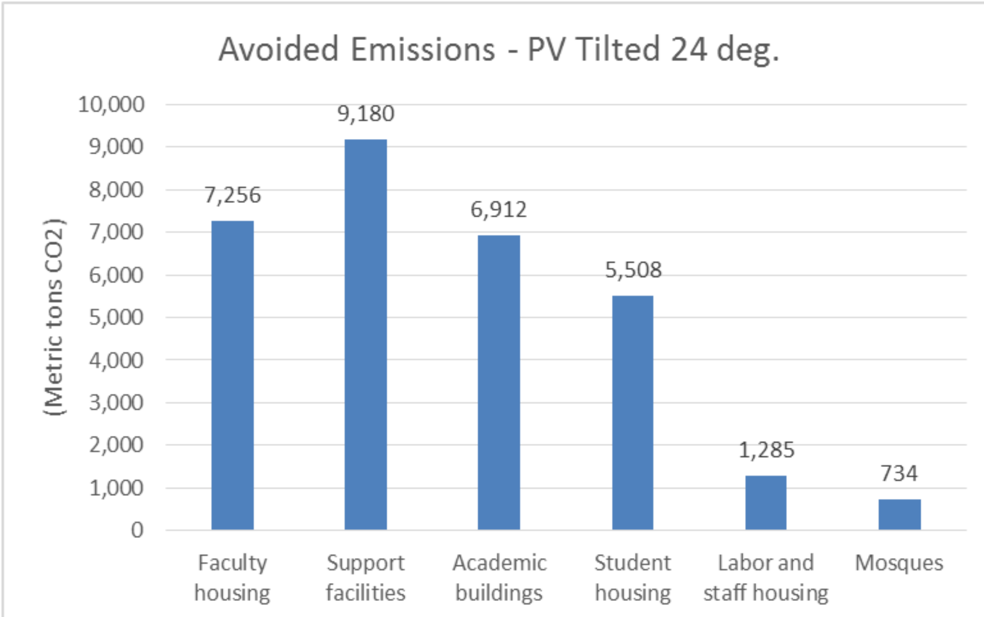


Figure 78: Avoided Emissions - PV Tilted 24°

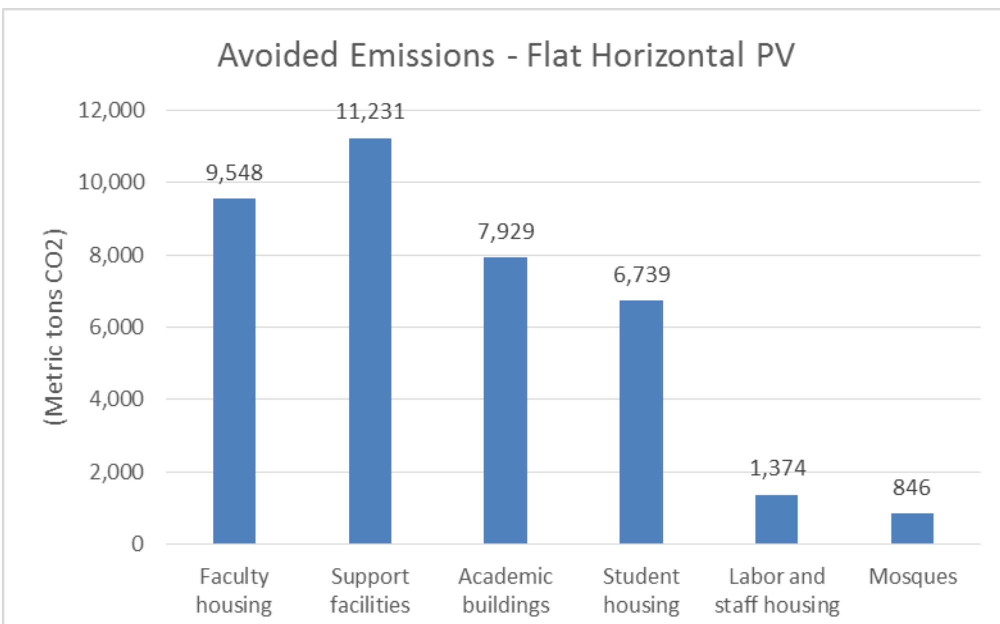
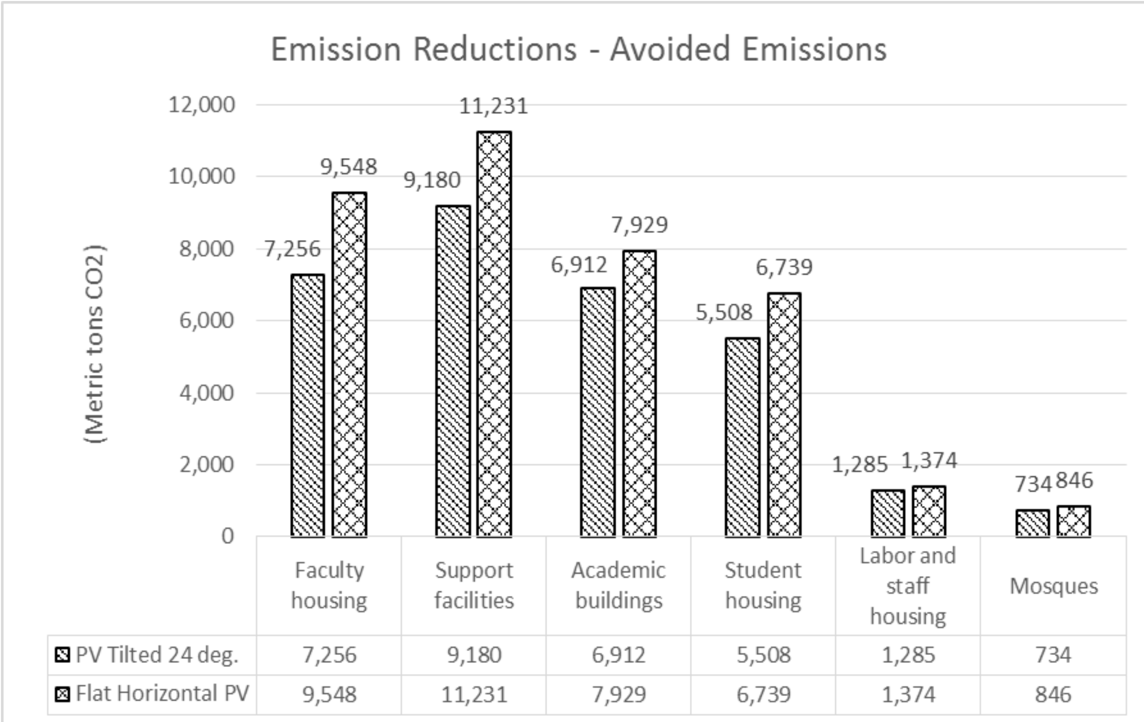


Figure 79: Avoided Emissions - Flat Horizontal PV



	Faculty housing	Support facilities	Academic buildings	Student housing	Labor and staff housing	Mosques
PV Tilted 24 deg.	7,256	9,180	6,912	5,508	1,285	734
Flat Horizontal PV	9,548	11,231	7,929	6,739	1,374	846

Figure 80: Emission reduction- Avoided emissions (Flat and Tilted PV panels)

The indirect emissions are shown in Figure 81, Figure 82, and Figure 83.

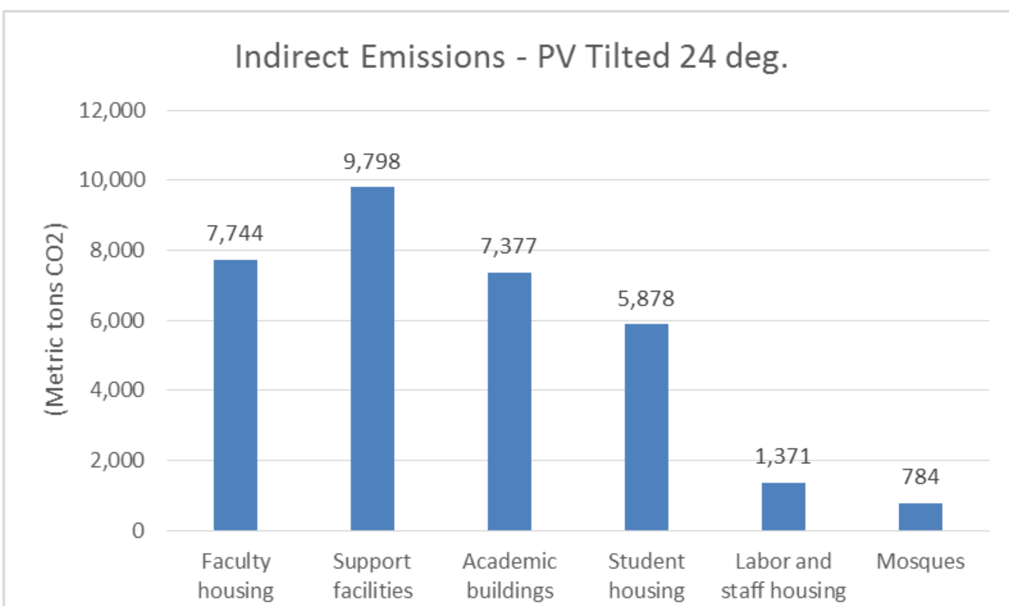


Figure 81: Indirect Emissions - PV Tilted 24°

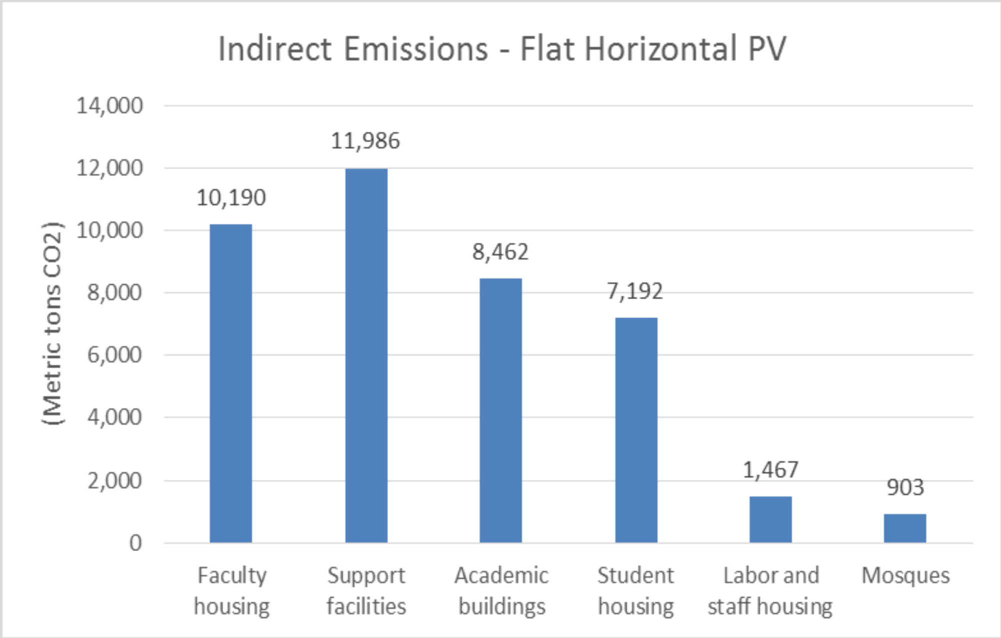
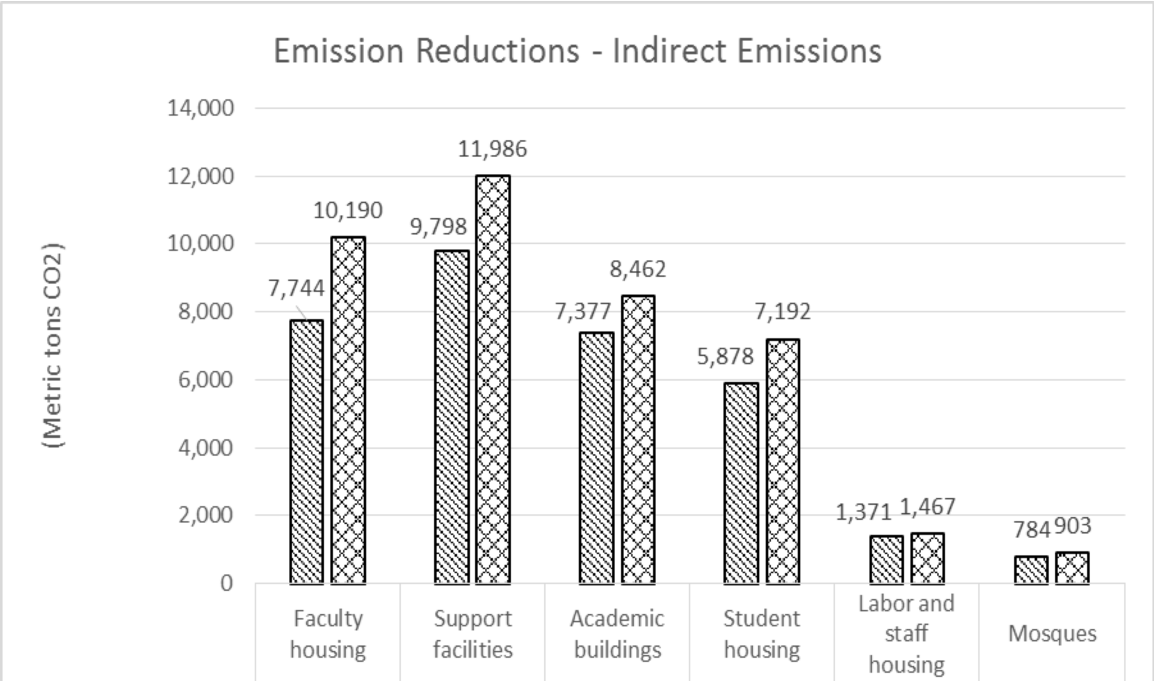


Figure 82: Indirect Emissions - Flat Horizontal PV



	Faculty housing	Support facilities	Academic buildings	Student housing	Labor and staff housing	Mosques
PV Tilted 24 deg.	7,744	9,798	7,377	5,878	1,371	784
Flat Horizontal PV	10,190	11,986	8,462	7,192	1,467	903

Figure 83: Emission Reductions - Indirect Emissions (Flat and Tilted PV panels)

4.7 KFUPM energy consumption

The electrical energy consumption of KFUPM's campus was obtained from the maintenance department at the university. Table 31, Figure 84, and Figure 85 show the annual electricity consumption and costs in KFUPM.

Table 31: Annual electricity consumption and costs in KFUPM

Year	Annual Consumption (MWh/year)	Annual Cost ($/year)
2003	175,242	12,147,760
2006	218,623	15,154,923
2009	185,406	12,852,333
2012	229,936	15,939,183
2013	216,591	15,014,120

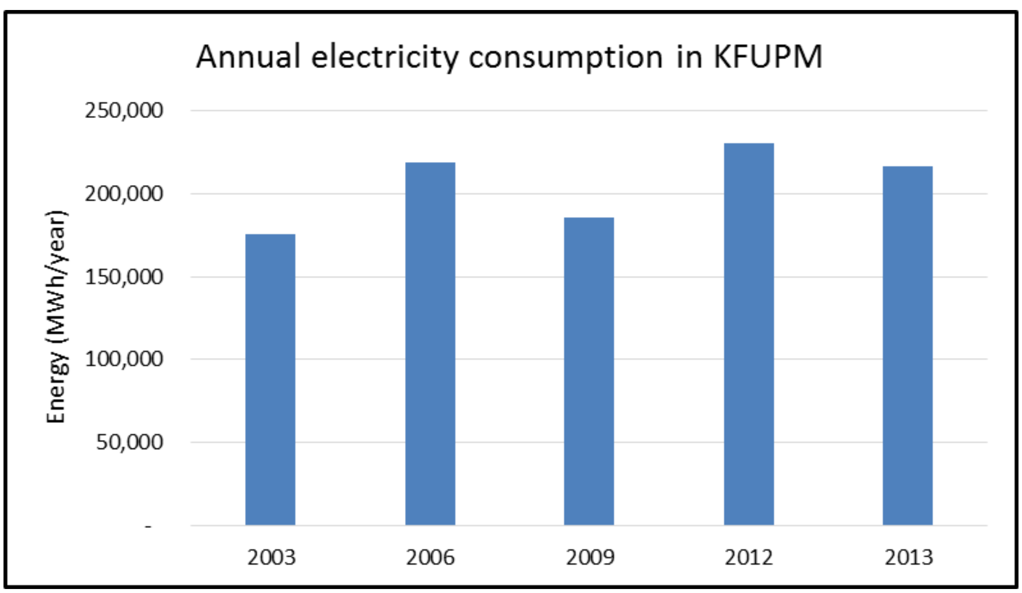


Figure 84: Annual electricity consumption in KFUPM

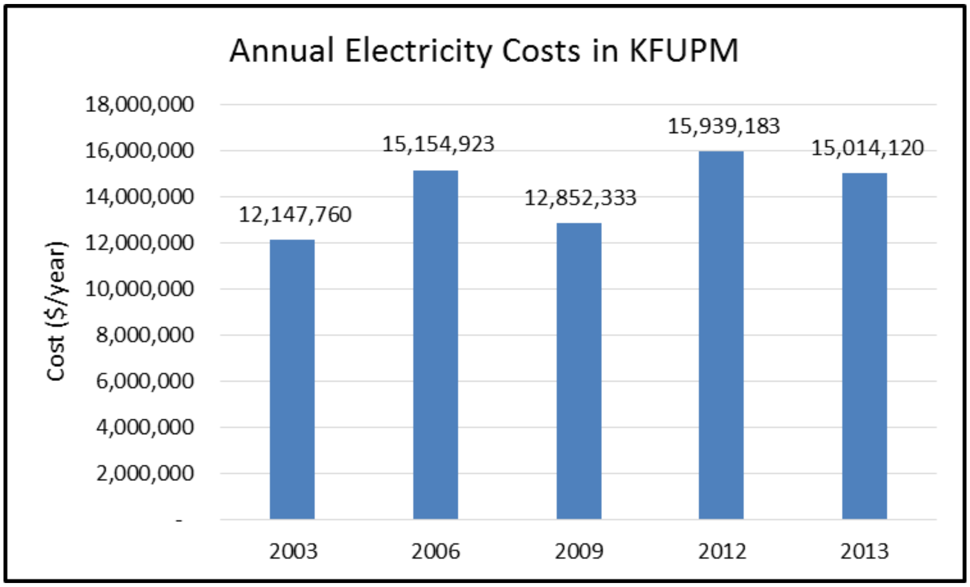


Figure 85: Annual Electricity Costs in KFUPM

It is obvious from Figure 86 that the electricity demand and consumption in KFUPM is following an increasing trend with time. It is expected that at the end of year 2015 that the electricity consumption will be about 230,000 MWh.

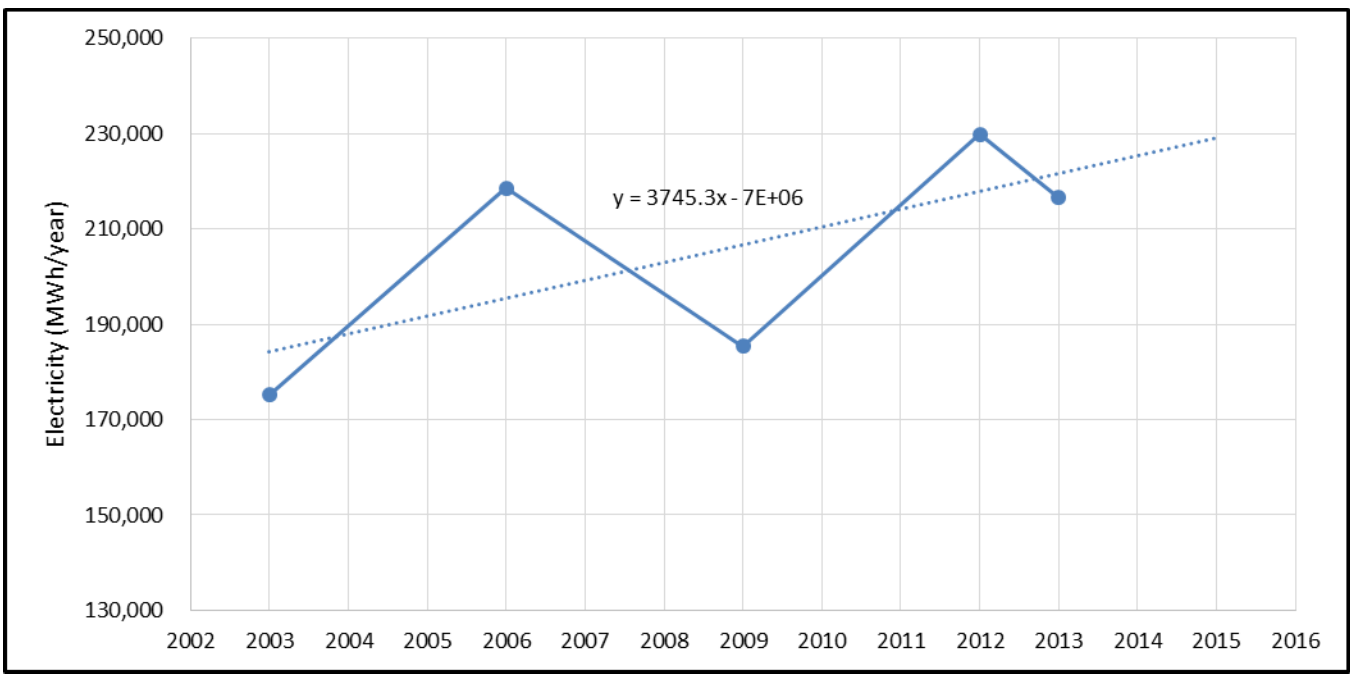


Figure 86: Electricity consumption trend forecasting for KFUPM

The summary results of the simulation processes of the rooftop photovoltaic systems in KFUPM are shown in Table 32. The potential of the total generated energy in KFUPM if the rooftop photovoltaic systems are tilted with 24˚ (optimal inclination angle) is 37,746 MWh/year; this is equivalent to \$2,616,553. On the other hand, the potential of the total generated energy if the rooftop photovoltaic systems are horizontal (flat with o tilt angle) is 46,047 MWh/year; this is equivalent to \$3,191,978 (knowing that each 1MWh costs \$69.32 in KSA).

With respect to Figure 86 that shows the electricity consumption trend forecasting for KFUPM, assuming that in the year 2015 the total electrical energy consumption will be 230,000 MWh/year, then this means that the generated energy will have the following percentage from the total consumption:

- For tilted PV panels:

$$\text{Percentage of generated energy from the total consumption} = \left(\frac{\text{Generated energy}}{\text{Total consumption}}\right) \times 100\%$$

$$\text{Percentage of generated energy from the total consumption} = \left(\frac{37{,}746}{230{,}000}\right) \times 100\% = 16.4\%$$

The distribution of the percentages of the generated energy from the total consumption over all the buildings' categories is shown in Figure 87 for tilted PV panels.

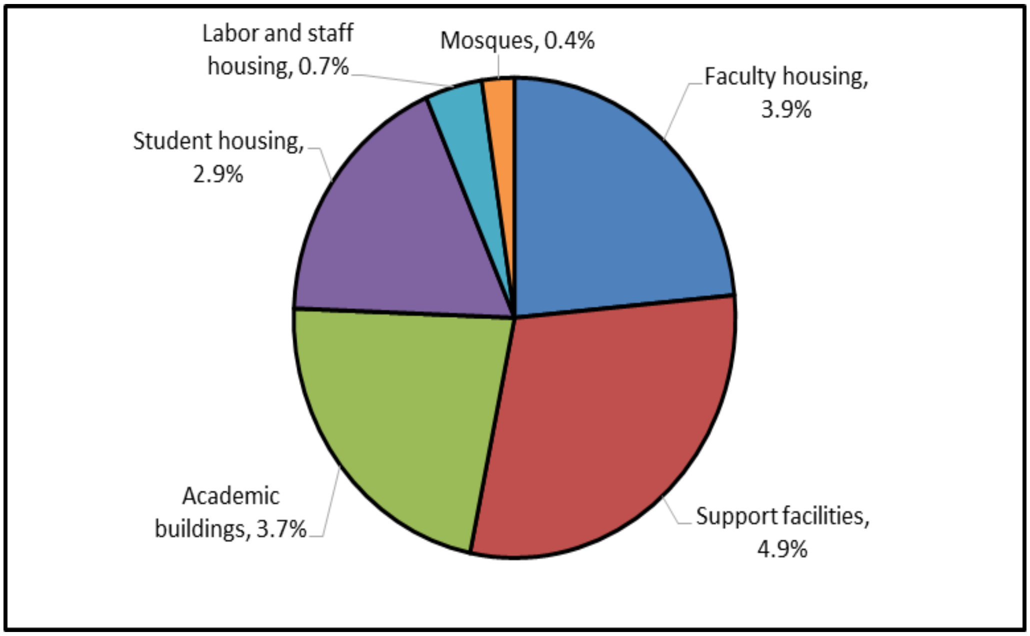


Figure 87: Percentages of the generated energy from the total consumption for tilted PV panels

- For horizontal PV panels:

$$\text{Percentage of generated energy from the total consumption} = \left(\frac{\text{Generated energy}}{\text{Total consumption}}\right) \times 100\%$$

$$\text{Percentage of generated energy from the total consumption} = \left(\frac{46{,}047}{230{,}000}\right) \times 100\% = 20.0\%$$

The distribution of the percentages of the generated energy from the total consumption over all the buildings' categories is shown in Figure 88 for horizontal PV panels.

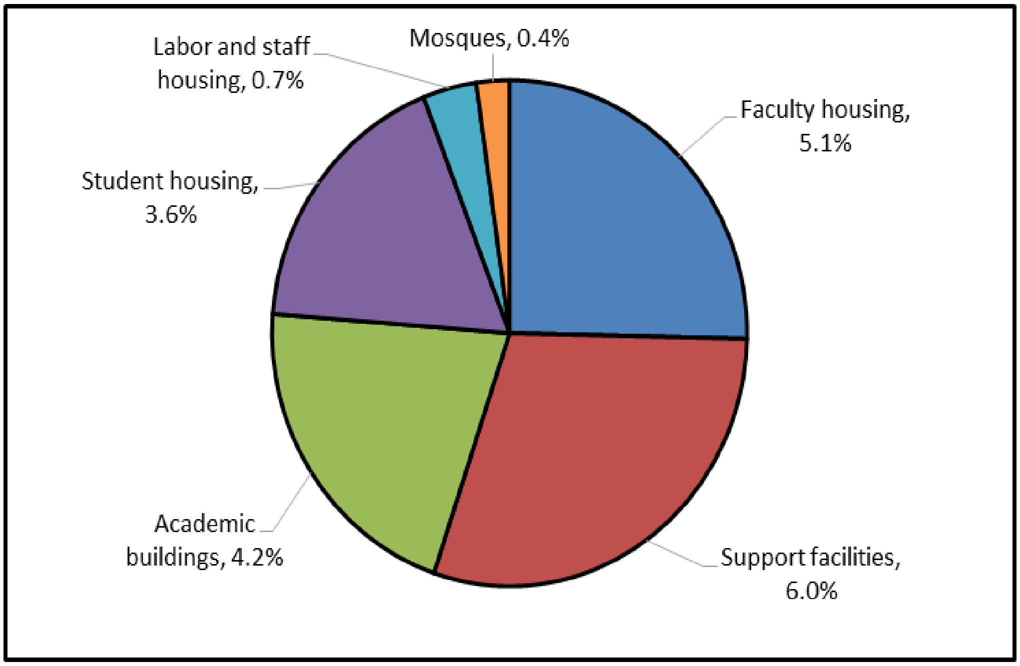


Figure 88: Percentages of the generated energy from the total consumption for horizontal PV panels

Table 32: Summary results of KFUPM's generated energy from rooftop PV panels

	Rooftop area	Produced Energy (MWh/year)	Benefit or Cost of Produced Energy ($/year)	Percentage of generated energy from the total consumption
PV Tilted 24°	Faculty housing	8871	614,938	3.9%
	Support facilities	11223	777,978	4.9%
	Academic buildings	8450	585,754	3.7%
	Student housing	6733	466,732	2.9%
	Labor and staff housing	1571	108,902	0.7%
	Mosques	897.9	62,242	0.4%
	Total	**37,746**	**2,616,553**	**16.4%**
Flat Horizontal PV	Faculty housing	11672	809,103	5.1%
	Support facilities	13730	951,764	6.0%
	Academic buildings	9693	671,919	4.2%
	Student housing	8238	571,058	3.6%

Labor and staff housing	1680	116,458	0.7%
Mosques	1034	71,677	0.4%
Total	**46,047**	**3,191,978**	**20.0%**

4.8 Temperature and dust effect on solar PV panels

The temperature of the solar photovoltaic panels is getting higher with longer exposure to sunlight and high ambient air temperature. The efficiency of the solar PV panels is negatively affected and decreased with the elevated temperature. This is due to the obstruction occurs for charge carriers as a result of the increased atom vibration (photons) (Baras et al., 2012). A study was conducted as part of Power System Program of the International Energy Agency (EIA) to investigate the relation between temperature and the photovoltaic efficiency. The study showed that the losses in efficiency was 1.7% to 11.3% as a result of temperature increase (Nordmann and Clavadetscher, 2003).

Another study was conducted on PV modules on Dhahran, Saudi Arabia. It showed similar effect of temperature on the efficiency. PV module efficiency decreased from 11.6% to 10.4% when module temperature increased from 38°C to 48°C, which corresponds to 10.3% losses in efficiency and a temperature coefficient of -0.11 ΔE/°C, see Figure 89. (Adinoyi and Said, 2013)

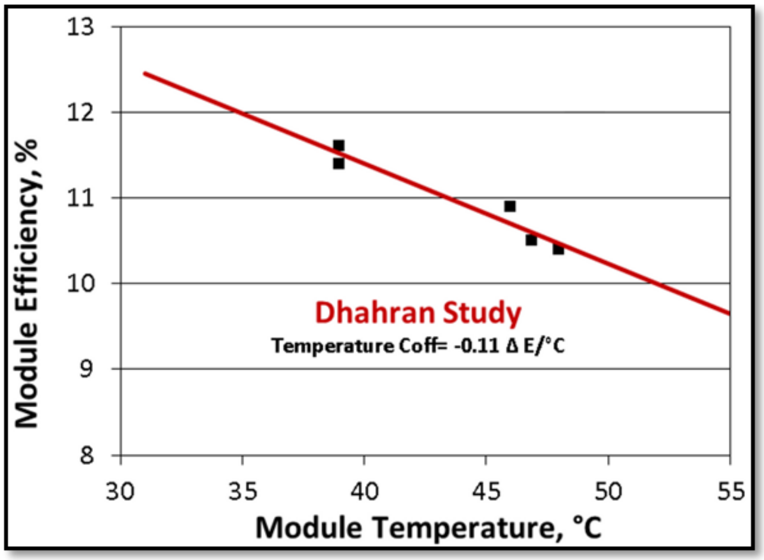


Figure 89: Relation between temperature and module efficiency in Dhahran. (Adinoyi and Said, 2013)

Saudi Arabia is frequently exposed to dust storms and dusty weather because of its location on a very arid region. Consequently, any solar photovoltaic PV system will have a relatively high opportunity for dust deposition on its glass surface. The dust in turn will reduce or sometimes block the solar irradiation form reaching the solar cells. The output power, current, and voltage will be inversely affected with dust density and accumulation. Adinoyi and Said 2013 conducted a study to find out the effect of dust accumulation on PV systems installed in Dhahran area. They came up with a conclusion that long period of exposure of PV panels to dust and outdoor conditions will gradually affect its output. The output power of the PV panels would be reduced by more than 50% if no cleaning is performed for six months.

4.9 Discussion

In this chapter, the following points may summarize the key results:

- The optimal inclination angle for Dhahran, Saudi Arabia is 24˚.

- Dhahran has good potential of solar irradiation on the optimal inclined surface of 7520 ($Wh/m^2/day$). Moreover, it has a direct normal irradiation of 1800 ($KWh/m^2/year$).
- The total rooftop areas of KFUPM buildings is 857,408 m^2. The rooftop areas of the parking buildings in KFUPM (352,244 m^2) cannot be utilized for PV panels installation because they are also utilized as parking lots. This will let KFUPM has 505,164 m^2 of rooftop areas.
- Optimization for energy generation was carried out for two cases of PV panels' installation: tilted PV with optimal angle, and flat or horizontal PV panels.
- KFUPM has a huge vast areas represented in its buildings' roof tops. These areas were estimated to be 171,310 m^2 if tilted PV panels were used. And 235,157 m^2 if flat or horizontal were used. These areas are ready for solar PV installation to generate electricity from the incident solar energy.
- Horizontal installation of PV systems makes better use of available roof area allowing larger number of PV panels to be installed compared to titled installation. Consequently, larger PV capacity can be installed horizontally, offering more energy generation than the tilted PV systems. Horizontal PV installation obviously would results into higher cost.
- Tilted PV systems provide higher BCR than the horizontal PV systems. The higher the BCR, the better the investment.
- Because the horizontal PV systems generate more energy than the tilted PV systems, this implies more protection to the environment from GHG emissions.
- Energy generation through tilted PV systems will save $2,616,553 and cover around 16.4% of KFUPM's total electrical energy consumption. However, the generation through the horizontal PV systems will save $3,191,978 and cover around 20.0% of KFUPM's electrical energy consumption.

CHAPTER 5

CONCLUSION & RECOMMENDATIONS

5.1 Conclusions

The kingdom of Saudi Arabia has rich potential for solar energy. Solar photovoltaic (PV) can be an appropriate technology to harness the immense solar potential. This study focused on the assessment of solar PV potential in KFUPM, one of the largest universities in the kingdom. It employed PVsyst and RETScreen programs to investigate the potential for solar PV on the rooftops of the entire campus buildings, offering 505,164 m^2 of rooftop areas. Optimization for PV installation was done for the power generation between tilted and horizontal PV systems. The following key conclusions are realized from the work.

- Dhahran area has around 1800 KWh/m^2 of average annual solar irradiation.

- The total rooftop area available through KFUPM buildings is 505,164 m^2. It is calculated that this area can accommodate 171,310 m^2 of PV panels installed at the optimum tilt angle for Dhahran. However for horizontal or flat installation, 235,157 m^2 of PV panels can be accommodated.

- Horizontal installation of PV systems makes better use of available roof area allowing larger number of PV panels to be installed compared to titled installation. Consequently, larger PV capacity can be installed horizontally, offering more energy generation than the tilted PV systems.

- The titled PV installation option can annually deliver 37,746 MWh of electricity while the horizontal installation can annually deliver 46,047 MWh of output.

- Tilted PV panels make better use of incoming solar radiation in terms of power output thus offering higher benefit to cost ratio than the horizontal or flat PV panels. Horizontal installation can accommodate larger capacity of PV system also demanding higher capital cost. It is observed that the BCR is greater than one for all of the areas except for labor & staff housing, and mosques. This indicates that these areas will be beneficial if they are invested with solar PV projects. The higher BCR is for the support facilities, faculty housing, academic buildings, and student housing respectively.

- The investment in PV systems would be profitable after the threshold of SPP, which only considers the total investment cost and the annual benefits of the project. However, for more precise consideration of time value of money, equity period could be used. The average of the simple payback periods for the investment in tilted PV panels is 13.5 years (excluding mosques which showed neither SPP nor equity periods in all cases). The average of equity periods is 11.7 years. On the other hand, the investment in flat PV panels has slightly longer periods, the average of simple payback periods is 14.2 years and the average of the equity periods is 12.2 year.

- If KFUPM utilizes tilted PV panels on its buildings' rooftops, it will save the environment from 30,876 tons CO_2 /year (avoided emissions) and 32,952 tons CO_2 /year (indirect emissions).

- If KFUPM utilizes flat or horizontal PV panels on its buildings' rooftops, it will save the environment from 37,666 tons CO_2 /year (avoided emissions) and 40,199 tons CO_2 /year (indirect emissions).

- Energy generation through tilted PV systems will save $2,616,553 /year and cover around 16.4% of KFUPM's total annual electrical energy consumption. However, the generation through the horizontal PV systems will save $3,191,978 /year and cover around 20.0% of KFUPM's annual electrical energy consumption.

5.2 Recommendations

The work leads to following key recommendations.

- It is important to adopt photovoltaic technology as a step forward to achieve sustainable and environmentally friendly energy and building sectors. Application of solar PV is becoming increasingly popular across the world and KSA can make use of its abundant potential in terms of rich solar radiation levels.

- KFUPM can significantly uplift the sustainability level of its campus in general and buildings in particular by installing rooftop PV systems.

- Horizontal PV systems will deliver more annual energy than the tilted PV systems as they cover more area of the roofs.

- In terms of finance and economic parameters:
    - Tilted PV systems have slightly higher BCR the horizontal systems.
    - Horizontal PV systems have slightly higher SPP.
    - Horizontal PV systems have slightly higher equity period.
    - Horizontal PV systems save more money each year than the tilted systems as they generate more e electricity.

- Horizontal PV systems save the environment from more GHG emissions than the tilted systems.

- The horizontal rooftop PV systems would offer more benefits than the tilted PV systems.

- The priority for the roof top PV utilization according to BCR is arranged as follows:
    1. Support facilities.
    2. Faculty housing.
    3. Academic buildings.
    4. Student housing.
    5. Labor and staff housing.
    6. Mosques.

5.3 Future work

Following areas can be worked on in future.

- Effect of shading from adjacent buildings.
- Façade integration of PV systems also looking into consequent impact on thermal performance of buildings.
- Application of solar tracking system.
- Effect of dust on the performance of PV systems.
- Investigating in the hybrid photovoltaic (HPV) technology, which generates electricity and heats the water. So, it makes two benefits at the same time.

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APPENDICES

Appendix A – technical specifications of the selected PV module.

Sunmodule™

SW 250 mono / Version 2.0 and 2.5 Frame

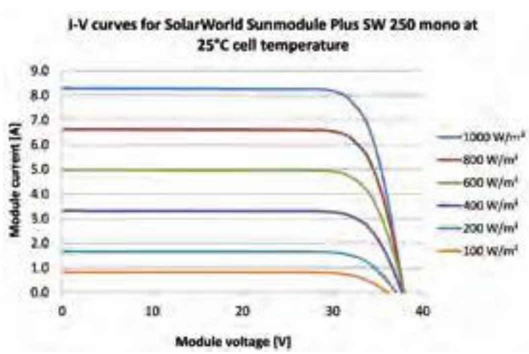
PERFORMANCE UNDER STANDARD TEST CONDITIONS (STC)*

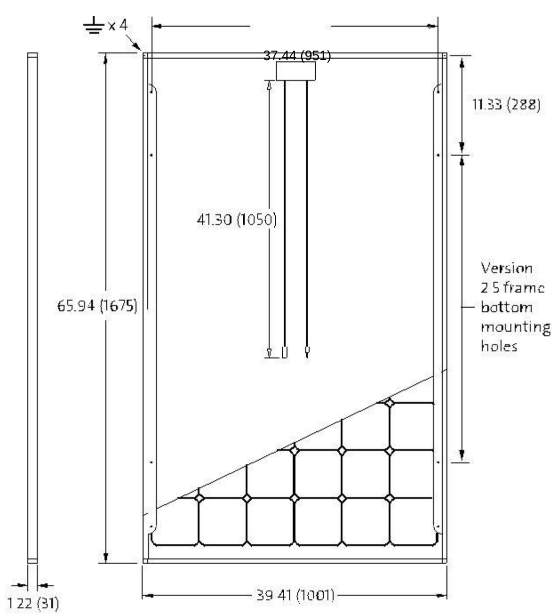
		SW 250
Maximum power	P_{max}	250 Wp
Open circuit voltage	V_{oc}	37.8 V
Maximum power point voltage	V_{mpp}	31.1 V
Short circuit current	I_{sc}	8.28 A
Maximum power point current	I_{mpp}	8.05 A

*STC: 1000W/m², 25°C, AM 1.5

THERMAL CHARACTERISTICS

NOCT	46 °C
TC I_{sc}	0.004 %/K
TC V_{oc}	-0.30 %/K
TC P_{mpp}	-0.45 %/K
Operating temperature	-40°C to 85°C





PERFORMANCE AT 800 W/m², NOCT, AM 1.5

		SW 250
Maximum power	P_{max}	183.3 Wp
Open circuit voltage	V_{oc}	34.6 V
Maximum power point voltage	V_{mpp}	28.5 V
Short circuit current	I_{sc}	6.68 A
Maximum power point current	I_{mpp}	6.44 A

Minor reduction in efficiency under partial load conditions at 25°C: at 200W/m², 95% (+/-3%) of the STC efficiency (1000 W/m²) is achieved.

COMPONENT MATERIALS

Cells per module	60
Cell type	Mono crystalline
Cell dimensions	6.14 in x 6.14 in (156 mm x 156 mm)
Front	tempered glass (EN 12150)
Frame	Clear anodized aluminum
Weight	46.7 lbs (21.2 kg)

SYSTEM INTEGRATION PARAMETERS

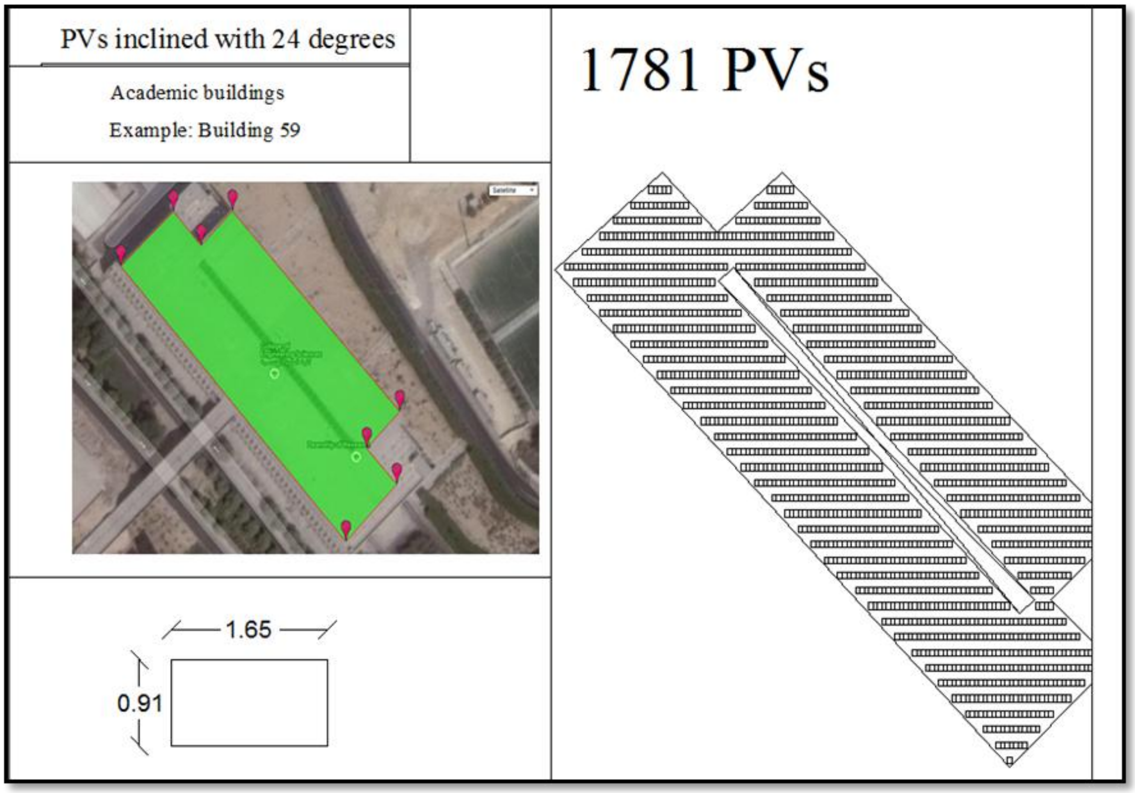
Maximum system voltage SC II		1000 V
Max. system voltage USA NEC		600 V
Maximum reverse current		16 A
Number of bypass diodes		3
UL Design Loads*	Two rail system	113 psf downward 64 psf upward
UL Design Loads*	Three rail system	170 psf downward 64 psf upward
IEC Design Loads*	Two rail system	113 psf downward 50 psf upward

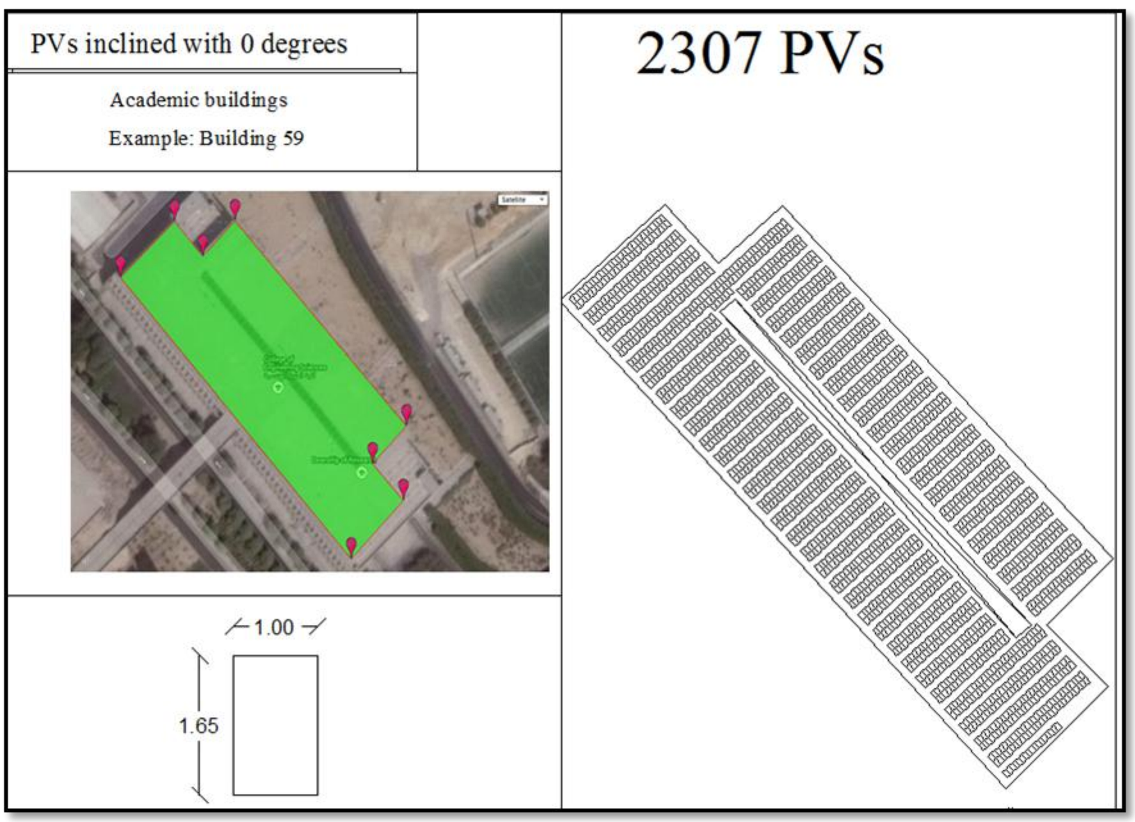
*Please refer to the Sunmodule installation instructions for the details associated with these load cases.

ADDITIONAL DATA

Power tolerance[2)]	-0 Wp / +5 Wp
J-Box	IP65
Connector	MC4
Module efficiency	14.91 %
Fire rating (UL 790)	Class C

Appendix B - Sample AutoCAD digitizing and PV drawing.





Appendix C – Sample simulation report.

PVSYST V6.34		30/03/15	Page 1/3

Grid-Connected System: Simulation parameters

Project :	**Grid-Connected Project at Dhahran (Academic Buildings)**			
Geographical Site	**Dhahran**		Country	**Saudi Arabia**
Situation	Latitude	26.3°N	Longitude	50.1°E
Time defined as	Legal Time	Time zone UT+3	Altitude	65 m
	Albedo	0.20		
Meteo data:	**Dhahran**	Synthetic - NASA-SSE satellite data, 1983-2005		

Simulation variant :	**Academic Buildings**	
	Simulation date	30/03/15 09h39

Simulation parameters					
Collector Plane Orientation		Tilt	24°	Azimuth	0°
Models used		Transposition	Perez	Diffuse	Erbs, Meteonorm
Horizon		Free Horizon			
Near Shadings		No Shadings			
PV Array Characteristics					
PV module	Si-mono	Model	**Mono 250 Wp 60 cells**		
		Manufacturer	Generic		
Number of PV modules		In series	16 modules	In parallel	1200 strings
Total number of PV modules		Nb. modules	19200	Unit Nom. Power	250 Wp
Array global power		Nominal (STC)	**4800 kWp**	At operating cond.	4261 kWp (50°C)
Array operating characteristics (50°C)		U mpp	434 V	I mpp	9816 A
Total area		Module area	**31236 m²**	Cell area	27302 m²
Inverter		Model	**12 kWac inverter with 2 MPPT**		
		Manufacturer	Generic		
Characteristics		Operating Voltage	350-600 V	Unit Nom. Power	12.0 kWac
				Max. power (=>25°C)	12.0 kWac
Inverter pack		Nb. of inverters	384 units	Total Power	4608.0 kWac
PV Array loss factors					
Thermal Loss factor		Uc (const)	20.0 W/m²K	Uv (wind)	0.0 W/m²K / m/s
Wiring Ohmic Loss		Global array res.	0.75 mOhm	Loss Fraction	1.5 % at STC
Module Quality Loss				Loss Fraction	-0.8 %
Module Mismatch Losses				Loss Fraction	1.0 % at MPP
Incidence effect, ASHRAE parametrization		IAM =	1 - bo (1/cos i - 1)	bo Param.	0.05
User's needs :		Unlimited load (grid)			

Grid-Connected System: Main results

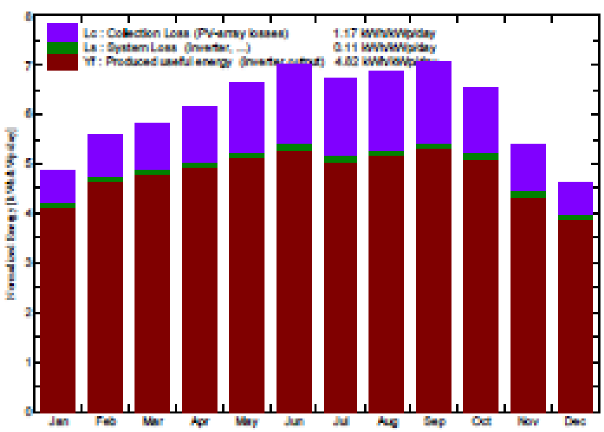
Project : Grid-Connected Project at Dhahran (Academic Buildings)

Simulation variant : Academic Buildings

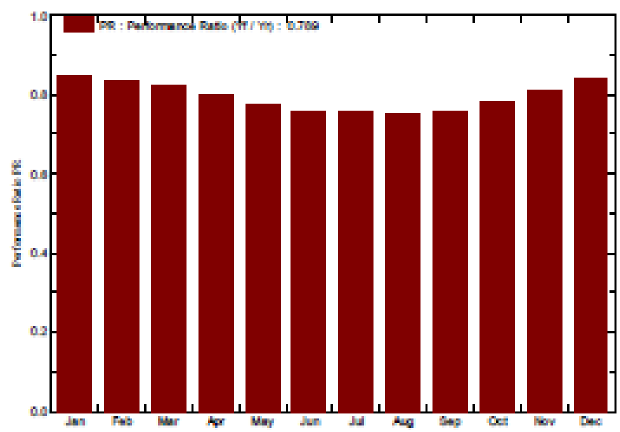
Main system parameters	System type	**Grid-Connected**		
PV Field Orientation	tilt	24°	azimuth	0°
PV modules	Model	Mono 250 Wp 60 cells	Pnom	250 Wp
PV Array	Nb. of modules	19200	Pnom total	**4800 kWp**
Inverter	Model	12 kWac inverter with 2 MPPT		12.00 kW ac
Inverter pack	Nb. of units	384.0	Pnom total	**4608 kW ac**
User's needs	Unlimited load (grid)			

Main simulation results				
System Production	**Produced Energy**	**8450 MWh/year**	Specific prod.	1760 kWh/kWp/year
	Performance Ratio PR	78.9 %		

Normalized productions (per installed kWp): Nominal power 4800 kWp



Performance Ratio PR



Academic Buildings

Balances and main results

	GlobHor kWh/m²	T Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray MWh	E_Grid MWh	EffArrR %	EffSysR %
January	110.7	18.65	151.4	147.5	630.6	616.6	13.33	13.04
February	123.8	19.29	156.2	152.4	640.7	626.0	13.13	12.83
March	159.0	21.52	180.6	175.8	730.9	714.2	12.96	12.66
April	180.9	25.80	185.0	179.8	727.3	710.5	12.58	12.30
May	217.9	30.78	205.3	199.2	782.1	764.2	12.20	11.92
June	231.9	33.63	209.7	203.4	779.2	761.6	11.90	11.63
July	225.1	35.12	207.9	201.7	771.5	754.0	11.88	11.61
August	216.1	35.20	213.5	207.6	787.8	769.8	11.81	11.54
September	193.5	33.12	212.0	206.8	785.1	767.6	11.86	11.59
October	165.2	29.75	203.1	198.2	775.5	758.5	12.22	11.96
November	120.0	25.36	161.6	157.5	641.3	626.8	12.71	12.42
December	101.7	21.09	143.7	139.9	593.4	579.8	13.22	12.92
Year	2045.7	27.49	2230.0	2169.9	8645.3	8449.7	12.41	12.13

Legends: GlobHor Horizontal global irradiation EArray Effective energy at the output of the array

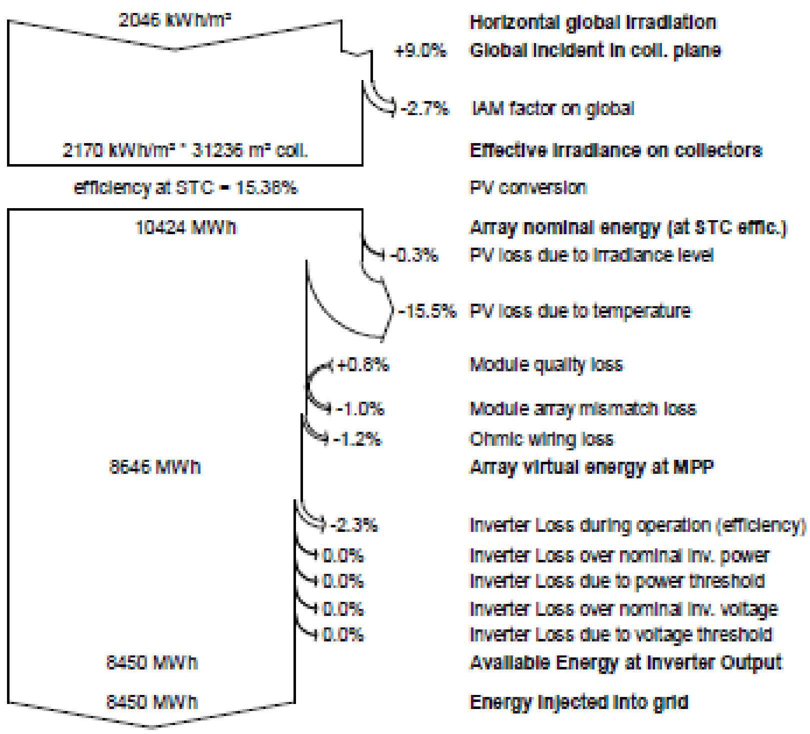
Grid-Connected System: Loss diagram

Project : Grid-Connected Project at Dhahran (Academic Buildings)

Simulation variant : Academic Buildings

Main system parameters	System type	**Grid-Connected**		
PV Field Orientation	tilt	24°	azimuth	0°
PV modules	Model	Mono 250 Wp 60 cells	Pnom	250 Wp
PV Array	Nb. of modules	19200	Pnom total	**4800 kWp**
Inverter	Model	12 kWac inverter with 2 MPPT		12.00 kW ac
Inverter pack	Nb. of units	384.0	Pnom total	**4608 kW ac**
User's needs	Unlimited load (grid)			

Loss diagram over the whole year



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